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Co-management is considered an alternative approach to fisheries management, however, not all co-managed fisheries have been successful. Most studies discussing the success and failure of co-management have emphasized economic and social attributes of success and failure, such as fishery rights and institutional arrangements. The effect on co-management of biological characteristics, such as the growth rate of the fish stock and the stock size, has gained little attention.

This study investigates the influence of intrinsic growth rate (r) and relative stock size (B') on fishers' decision to cooperate with catch quotas. The concept of mixed strategies from game theory is incorporated with basic economic concepts and a biomass dynamics model to capture important aspects in a fishery cooperative. The discounting concept is applied to capture the fishers' tendency to cooperate (δ_i). Profits from fishing are specified for each fisher within a 2 by 2 matrix with two players and two strategies (cooperative and non-cooperative). When both players have dominant strategies, where one player's best strategy coincides with the other player's best strategy, the game has a

pure strategy equilibrium. Alternatively, the equilibrium outcome of the game is determined using mixed strategies.

The results indicate that the biological parameters, r and B', influence fishers' cooperation. However, social parameters (δ_i) and economic parameters (profit/cost ratio when the stock is at the carrying capacity) must also be considered. Furthermore, this study finds that the fishers are more likely to play the cooperative strategy over very wide ranges of r and B' when their tendencies to cooperate are high. In contrast, the fishers are more likely to play mixed strategy when their tendencies to cooperate are low. Having a large discrepancy between the fishers' tendencies to cooperate has less influence on the outcomes of the game than having high values for the fishers' tendencies to cooperate. The profit/cost ratio generally accentuates the most frequent outcomes of the game. For instance, if the outcomes are mostly mixed strategies, a higher ratio expands the mixed strategy outcomes over wider ranges of r and B'.

The Influence of Biological Characteristics on Fisheries Co-management: A Game Theory Perspective.

By

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Jiraporn Trisak, Author

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In the memory of my father and grandmother

who could not wait until this day to come.

THE INFLUENCE OF BIOLOGICAL CHARACTERISTICS ON FISHERIES CO-MANAGEMENT: A GAME THEORY PERSPECTIVE

I. INTRODUCTION

The main aim of this study is to investigate whether certain biological characteristics of an exploited fish stock influence fishers' decisions to cooperate with other fishers. This study focuses on fishers' behavior in a fishing cooperative organization where fisheries co-management is practiced. Under the particular co-management arrangement the fishers receive shares of a catch quota issued by a central authority but the fishers may decide to cheat and catch more than their quota shares, in which case the co-management system has failed. The study examines factors that might cause such internal conflict among the members, which is one serious problem in co-management (Jentoft, 1989). To resolve this problem it is important to understand the key factors that may influence cooperative commitment and cause internal conflict among the members. This thesis hypothesizes that the biological parameters of the fish stock may play a crucial role in influencing fishers' cooperation.

Fisheries co-management is an alternative to centralized fisheries management in which only a government authority has full responsibility for management. It has been recognized that centralized management gives rise to illegitimacy because of the restrictive fishing regulations that management imposes on fishers' behavior (Nielsen and Vedsmand, 1997; Noble, 2000; White and Mace, 1988;). The restrictive regulations are a product of the well known open access fisheries paradigm, which portrays the fishers as self-interested and whose actions jeopardize the fish resources. The only way to prevent overexploitation of the resource is by imposing regulations to control the fishing activity

(Jentoft, 1989). Under an open access fishery, fishing regulations, which aim to protect the biological sustainability of the fish stocks, are restrictive on how, which, when, where, and how many fish may be caught (Kahn, 1995). The restrictive regulations contradict the fishers' interests of maximizing their profits and, hence, become unacceptable for the fishers. In contrast, fisheries co-management is an arrangement whereby the government and the fish resource users jointly share responsibility, including decision-making (Hanna, 1995; Jentoft, 1989; and Pinkerton, 1989). The fishers have a chance to express their opinions and concerns, participate in the decision making process, and bring in legitimate regulations.

STATEMENT OF THE PROBLEM

Fisheries co-management has the potential for solving certain problems of fisheries management, but in practice some fishing communities have had unsuccessful experiences with co-management (Pinkerton, 1989; Pollnac and Carmo, 1980). Several studies have attempted to analyze cooperative behavior to determine why co-management is not always successful. Most of the studies have been descriptive. They address and discuss economic and social concerns as factors in either the success or failure of co-management. Examples are the studies of Hanna (1995), Jentoft (1989), Kuperan and Abdullah (1994), and Pinkerton (1989), which address the merits of co-management and are concerned about preconditions for the success of co-management. The potential merits of co-management commonly discussed in those studies include: resource sustainability; easier implementation and enforcement; less conflict among resource users; and lower cost of sharing the fisheries resources for the users. However, none of the published studies have examined the role of biological factors on the cooperative behavior of fishers. The fishers' behavior may be affected by their knowledge about the fishery resources.

The analytical studies have been confined to the problem of conflicts between co-owners of transboundary fish stocks. A transboundary fish stock is a highly migratory fish stock, a fish stock found in the coastal Exclusive Economic Zone that is shared by more than one nation, or a fish stock that is categorized as a straddling stock (Kaitala and Munro, 1995; Rettig, 1995). Neither country completely owns the stock--each has control over the stock only during the time when the stock is present in its waters. These studies have applied the theory of differential games to account for the dynamic aspects of the fish stock in order to explore conflicts between the two countries that share the stock. The goal of these studies was to define optimal harvests so that a cooperative agreement could be reached. They did not directly investigate the effect of biological factors on cooperative behavior.

Fishers may have good intuition about trends in the growth characteristic of a fish stock; they may have a sense about whether it is worthwhile to commit to a cooperative organization. For example, if the future is uncertain, as with a stock having a fast but variable growth rate and short life span, such as shrimp, shell fish, and squid (Nagasaki, 1993), the fishers might be unsure that the reward from cooperating would outweigh the costs. In addition, fishers normally try to maximize their profits in the short term so that they can pay off their debts (Townsend and Pooley, 1995; Cunningham, Dunn, and Whitmarsh, 1985). In contrast, fisheries co-management aims at the long-term goal of resource sustainability. Under variable environmental conditions a fish stock has both bad years and good years. During a bad year, managers would want to reduce the catch or even to prohibit fishing to enhance the rebuilding of the stock. The question is whether the fishers can accept the risk of long-term responsibilities of cooperative management when they need money to pay off their debts. Therefore, the fishers' attitudes towards risk may be an important influence on their decision to cooperate, especially given great uncertainty about future conditions in the fish stock.

According to Marwell and Schmitt (1975) cooperation that implies joint access or control over resources has different types of risks, which strongly influence the tendency of resource users to cooperate with each other. For fisheries there are risks associated with changes in the fish stocks. In a study of Pollnac and Carmo (1980), risk concerning changes of the resource had an impact on the tendency of fishers to cooperate with each other. The higher the uncertainty concerning changes in the resources the lower the tendency to cooperate. Specifically, they found that when the fish resources became scarce due to the pressure of heavy exploitation the fishers perceived high risk concerning the status of the resource and consequently were less cooperative.

The biological status of the resource will be uncertain due to changing environmental conditions or variation in population parameters such as growth or reproduction. Therefore, the fishers' tendencies to cooperate could be influenced by the uncertainty of the fish resources due to variable biological factors. Certain characteristics of a fish stock, such as either low abundance or high variability in its natural productivity, will contribute to a perception of high risk, which decreases the fishers' tendency to cooperate.

Another type of risk that an individual fisher may face is the risk that other fishers will overexploit the resources. This type of risk induces interpersonal distrust, which also decreases the tendency to cooperate (Pollnac and Carmo, 1980). The fishers would want to cooperate if they could expect the others to do the same.

Because risk preference often differs among individuals (Luce and Raiffa, 1957), the fishers may have different responses to risk and, hence, different tendencies to cooperate. The fishers who are more willing to gamble on the uncertainty of the stock are risk takers. Because of their willingness to bear the risk of uncertainty in the fish stocks, these fishers would believe that they could do better by themselves rather than by joining a cooperative organization, hence they have less tendency to cooperate. In contrast, those fishers who are less willing to gamble on the uncertainty of the stock are risk averse. They perceive that the benefit from joining the cooperative outweighs the benefit from operating outside the cooperative. Different risk preferences among the fishers means that the fishers are heterogeneous. Heterogeneity in the fishers' risk preference could contribute to lack of trust and result in the breakdown of the cooperative arrangement.

One common criticism of standard game theory models is the unrealistic assumption that the players are homogeneous, that the players do not differ in their tastes, information, and culture (Rasmusen, 1992; Wildavsky, 1992; Tullock, 1992). When a modeler applies game theory he could fail to capture the different perceptions that could be a key factor in the players' decisions to choose particular strategies. The modeler might actually distort the potential strategies selected by the players and, consequently, falsify the solution of the game. Therefore, any conclusion from a study applying game theory would be invalid when pertaining to a situation involving heterogeneous players.

With regard to the problems I have outlined, I hypothesize that biological parameters may have an influence on fishers' decisions to cooperate. Furthermore, I propose that we need to apply game theory in a more specific and appropriate manner that makes explicit provisions for heterogeneous players. The problem of ignoring player heterogeneity is not a failure of game theory, but a lack of appreciation about the nature of human heterogeneity on the part of the modelers or researchers. Game theory can be applied to many situations, including player heterogeneity (Rasmusen, 1992). Therefore, applying game theory in the study of a conflict situation among heterogeneous players is plausible. However, a specialized game specific to the situation will need to be developed to address these crucial aspects.

OBJECTIVES

The general goal of this research is to understand cooperative behavior of fishers with respect to co-management. This research will focus on why fisheries co-management works in some circumstances but not in others.

The specific objectives of this research are:

1. to use game theory to investigate how biological factors influence whether fishers will remain in a cooperative management arrangement under which all fishers receive equal shares of a fishery catch quota; and
2. to apply game theory to the situation in which the players are heterogeneous in their attitudes towards risk and, hence, their tendencies to cooperate.

ORGANIZATION OF THE DISSERTATION

This study is divided into 6 chapters. The first chapter, the introduction, includes a statement of the problems and objectives of the study. Chapter 2 is a literature review of the published background information needed for the analysis. Chapter 3 is the analytical framework that presents the scope of the analysis and the general information and theoretical concepts applied in the analysis. Chapter 4 is the analyses of the fishery game, given various scenarios related to combinations of the parameters in the fishery game. Chapter 5 discusses the set of scenarios that illustrate the influence of biological parameters on fishers' decisions to cooperate. Chapter 6 presents conclusions drawn from this study, some recommendations for future studies, and general suggestions for fisheries co-management.

II. LITERATURE REVIEW

CO-MANAGEMENT/COMMUNITY-BASED FISHERIES MANAGEMENT

DEFINITION

Community-based fishery management is rooted in the concept that the community takes responsibility for monitoring and enforcement of management plans. However, it is unlikely that communities can successfully implement fisheries management on their own (Pomeroy, 1994). The government must be involved as a co-manager with the communities. Despite being knowledgeable about their resources, the fishers need financial support and guidance in managing their communities. In its broad context, co-management is joint management through a cooperative organization of government and resource users (Hanna, 1995; Jentoft, 1989; and Pinkerton, 1989). Co-management involves decentralized control in which the government and the communities share management responsibilities and the initiation of regulations. Communities participate in the decision-making process, and make and implement the regulations. Communities are involved in determining fisheries management measures, supervising their implementation and invoking penalties when management measures and guidelines are ignored (Doulman, 1993).

The terms, co-management and community-based management are interchangeable (Kuperan and Abdullah, 1994; Pinkerton, personal communication). They both refer to management in which the community plays a major role and holds significant power to make decisions. However, there is no universally accepted definition of either co-management or community-based fisheries management (Lim, Matsuda, Shigemi, 1995; Yamamoto, 1995).

BACKGROUND ON COMMUNITY BASED FISHERIES MANAGEMENT (CBMF)

Centralized management has been the traditional management tool for fisheries resources. However, it has rarely been successful because of failures in implementation and enforcement (Jentoft, 1989; Pinkerton, 1989; Hanna, 1995). Most fisheries regulations have been established based upon a government's perspective towards the fisheries resource, which is typically focused on resource conservation. The regulations restrict fishing activities, which can result in higher costs for fishers. For example, a regulation restricting the fishing season may lead fishers to invest in better technology so they can catch enough fish within the shorter season, which leads to a competitive race for fish.

Many countries have sought alternative management approaches because their resources continue to be depleted in spite of having a centralized management system. Resource managers recognize that many coastal communities from various parts of the world have been very successful at self-regulation (Lewis and Cowens, 1982; Berkes, 1985). Fisheries regulations made by the people in the community are based upon the fishers' perception of the fish resource and the prevailing environmental conditions that the fishers experience. Under these circumstances, it is easier for the fishers to adopt regulations established from their perspective because they perceive them as being fair (Jentoft, 1989). The recognition of successful self-regulation, combined with evidence of stock depletion and the failures of centralized management have encouraged community planners, development workers, anthropologists, biologists, geographers, and environmental scientists to develop both the theory and the practice of community-based management (Berkes, 1985; Jentoft, 1989). This form of management has been of particular interest to many fisheries organizations, including the Fisheries Department of the Food and Agriculture Organization (FAO) of the United Nations.

EXAMPLES OF COOPERATIVE ORGANIZATIONS

Most of the published literature addresses and discusses only social and economic concerns in the success or failure of co-management, such as social and economic equity. Co-management participants voluntarily cooperate if they perceive fairness in being cooperative. Concerns about the biological status of the resource have been addressed only broadly in terms of resource sustainability--sustainability is required as a precondition of success. None of the literature expresses concern about how the fishers may respond to the uncertainty of the resource, which, in turn, is likely to affect resource sustainability. Most fishing problems in co-managed fisheries are caused by conflicts and competition among the cooperative organizations' members (Weinstein, 2000). These problems could possibly be driven by different responses to the uncertainty regarding resource status among the members of the cooperative.

Despite the limited information available from the published literature, I will give some examples to demonstrate the potential significance of biological parameters on co-management, specifically on fishers' decisions to cooperate. The examples are Japanese Fisheries Cooperative Associations (FCAs), some of which have successful co-managed fisheries and some have had failed attempts at co-management. The relative success of co-management is considered with respect to its degree of competition and conflict--the more successful the co-management the less competition and conflict among the participants.

Selecting case studies only from the Japanese co-managed fisheries reduces the influence of differences in ethnicity, culture and environment when making a comparison between the more and less successful cases. There is evidence that the cultural background and norms of fishers are factors that influence the success of co-management. As acknowledged by Lim, Matsuda and Shigemi (1995), compliance behavior, conflict avoidance and cultural values are important to the Japanese, and are factors contributing to the success of Japanese co-management. The Japanese tend to be respectful and obedient to regulations. They tend to compromise and prefer to avoid conflict. Their cultural values give them strong spirit in committing to collective values and participatory decision-making in management.

In order to understand more about the Japanese co-management system, I give some brief and general information on historic and present day Japanese FCAs and, subsequently, some examples of FCAs. The details on the evolution of Japanese fisheries co-management, fisheries law, and cooperative organization are well documented in the literature, including Ruddle (1985), Kawaguchi and Naruko (1993), Hirasawa (1993), Yamamoto (1993) and (1995), Lim, Matsuda, and Shigemi (1995); and Weinstein (2000).

Throughout this paper, the terms co-management and community-based fisheries management are used interchangeably. However, most of the reviews of the Japanese fisheries management use the term community-based fisheries management, therefore, I will use that term exclusively in this section.

Japanese Community-based Fisheries Management and Fishery Cooperative Associations

Japanese community-based fisheries management (CBFM) has been developed mainly for coastal and near-shore fisheries. Particularly with the Japanese, CBFM refers to a management system that is initiated by fishers. Most CBFM systems deal with inshore fish resources, particularly sedentary species such as abalone, top shell, spiny lobster, sea urchin, and clam. A few CBFM systems deal with migratory species, such as Kuruma prawn, mantis shrimp, red sea bream, and flat fish (Yamamoto, 1995). The goals of CBFM systems are mainly the effective use of fishing grounds and market-oriented measures. This traditional form of management has been practiced since 1743 (Yamamoto 1995). Japanese fisheries management, which has been evolving for more than 250 years, can be classified into three periods: the Feudal era, the Blank Period without fishery law, and the Old Fishery Law Period. In the Feudal era (1743-1867), the first Japanese fishery law (Ura Law) was enacted. Fishing rights were granted to fishing villages along the Japanese coast. However, the main purpose of those fishing rights was for tax collection.

During the Blank Period (1868-1900), the Japanese government (the Meiji Government) tried to modernize their country and introduced Western concepts to many fields, including governance, economics, education, technology, and fisheries management. As a result, the ownership of fisheries reverted to the central government in 1876 (Ruddle, 1985). For 32 years Japanese fisheries management followed Western resource management practices, mainly based on open access fishing in which everyone has access to the fish resources. This type of management practice consequently gave rise to conflict among the fishers (Weinstein, 2000; Yamamoto, 1995; Ruddle, 1985).

The period of Old Fishery Law was from 1901 to 1948. After the disappointing Blank Period, the Japanese restored their traditional fishery management practice (Yamamoto, 1995). The government established new fishery laws based solely on the traditional management that was practiced in the Feudal era. Every fishing village was required to have a Fishery Society (FS) that was granted fishing rights. Only the members of the FS could participate in that fishery.

In 1933, the government tried to improve fishers' incomes and their living conditions. The infrastructure of Fishery Societies was changed to allow the fishers to get more involved in the management, especially in marketing. Consequently, fishing rights were transferred to Fishery Cooperative Associations (FCA) in 1948. Under the Fisheries Cooperative Law, each fishing village was required to establish its own FCA whose fishing rights and licenses were granted within its territory. The FCAs were responsible for establishing fishing zones, seasons, gear, and methods of fishing. In addition, the FCAs supported their members in terms of marketing, the supply of fishing gear, and banking.

Current Fishery Law (1949-present) came formally into effect with the reform of fishing rights in which the central government granted control of the FCA's to the prefectural governments (Weinstein, 2000; Yamamoto 1993,1995; Ruddle, 1985). A prefectural government is a local government, equivalent to a state or provincial government. There are 47 prefectures in Japan, each of which has it own government. Within a prefecture, the fishing area is grouped into two or more regions based upon homogeneity of environmental conditions and the fish resources. A regional fisheries coordination committee, consisting of 16 members, 9 elected from fishers and 7 appointed by the prefectural government, is responsible for a coastal fisheries management plan (CFMP). The committee serves on behalf of the regional fishers' interest and also acts as a consulting committee for the prefectural government. Each FCA establishes regulations and also implements the control and operation of various groups of fishers in an equitable, efficient and sustainable manner, as local conditions dictate. Even though the FCAs have the primary authority for regulating the fisheries, all regulations have to be agreed to by all parties involved in management, including central and prefectural government staffs, individual FCAs' members and their fishery groups.

The main management techniques for the Japanese community-based fishery management are fishing rights and fishing licenses. The fishing rights are specifically for coastal fisheries, while the fishing licenses are for offshore and distant water fisheries. Fishing rights are rights to participate in fishing activities that are specified for a particular fishery within a certain area. Under the fishery cooperative law, each FCA has a committee called the FCA Fishing Right Management Committee (FCA FRMC) that develops a fishing rights plan and proposes the plan to the prefectural government.

From the establishment of FCAs in 1948 to 1988, the Japanese community-based fisheries management was done on a case-by-case basis (Hasegawa, 1993; Yamamoto, 1995). Formal nationwide community-based management began in 1988 when the Fishery Census, which is conducted every five years, defined a fisherman-initiated Fisheries Management Organization (FMO). The FMO includes two components: (1) fishers who are engaged in the same mode of fishing, such as within the same fishing gear type and class of boat, or who share a common fishing ground; and (2) management aimed at collective management of the fish resources, fishing grounds and fishing operations. Most of the FMOs are formed under the initiative and guidance of FCAs. Hence, there is a close relationship between FCAs and FMOs. The Fishery Census classifies this relationship into four categories (Hasegawa, 1993): (1) a FMO is managed by a FCA or it is the FCA by itself; (2) a FMO is formed by fishers with regard to the fisheries cooperative law; (3) a FMO is organized by the will of the members of fisheries cooperatives; and (4) a FMO is founded by other organizations.

In sum, Japanese community-based fisheries management is a collaborative management of FCAs and their affiliates, including central government, and prefectural government. The FCAs are responsible for distributing fishing rights to their members, including conducting business activities under fishery cooperative law such as obtaining or giving credits to their members, marketing, guidance (education and leadership development activities) and supporting services (such as ice manufacturing, freezing and cold storage).

More Successful FCAs

A unique characteristic that is the main reason for the success of the Japanese community-based fisheries management is ownership of rights to fishing territory (Lim, Matsuda, and Shigemi, 1995). Fishers have incentive to fish conservatively being the owners of the resources. In addition, exercising co-management specifically to sedentary resources within a coastal area contributes to the success. The combination of being limited to coastal fishing areas and relatively immobile species makes it easier to clearly specify the ownership of fishing rights, which consequently reduces conflict and competition among fishers or fishery groups. The less conflict and competition among the members, the more successful the co-management (Yamamoto, 1995).

The following case studies concern the Nomaike FCA (Lim, Matsuda, and Shigemi, 1995) and the Katsuura FCA (Katsuura Fishermen's Cooperative Association, 1992). Both cases were selected because these FCAs have been successful and because there is information on co-management as well as basic information on the fisheries. They also indicate a possible correlation between fish stock characteristics and fishers' cooperation.

The Nomaike FCA. Founded in 1949, the Nomaike FCA is a successful Japanese FCA, with few conflicts among its member throughout the history of the association. There are many kinds of fishery in the fishing villages of the Nomaike FCA, including pole, line, set-net, marlin drift net, and gill net. Most of the fisheries are small-scale, family businesses. The biggest portion of the catch is sardine, accounting for 14% of the landing. Other species that are frequently caught are yellowtail, chicken grunt, bonito, mackerel, flying fish, and filefish. Fishers also target high priced species, such as yellowtail larvae, young yellowtail, abalone, lobster, scorpion fish, flatfish, Japanese parrotfish, sawedge perch, and sea bream.

Formally, most fishing regulations are not highly detailed and restrictive. In practice, however, there are rules that restrict fishing operations. For example, there are no formal regulations defining fishing areas and seasons for sedentary species, such as abalone, spiny lobster, sea urchin, and Japanese ivory shell. But practically, the fishers themselves set the fishing rules on fishing area and season, including specification of fishing gear (such as length, height, and mesh size for set net).

Despite its success with few conflicts, the Nomaike FCA has been facing a problem of a lack of new fishers. The membership has declined since 1960, from 572 members to 377 members in 1992. The main reason for the decline is low productivity of the fish stocks. Young people have been forced to move into the big city for better paying jobs because of the lack of alternative jobs within their prefectures and encouragement from their parents. Being aware of the risks of the fishing business, most parents believe that other jobs would be better for their children than fishing.

The Katsuura FCA. The popular fishery in Katsuura is lobster, which spreads along the Pacific coast of Katsuura city, in the Wakayama prefecture. The fishing season is from September 10 to April 30, but intense fishing occurs during a short 10 to 20 day period from November to December. The lobsters are fished mainly by bottom gill net. Management measures for the lobster fishery are limited entry and a pool account system. The limited entry was established by a group of lobster fishers in 1959, after a period of decreasing catch in the 1940s and 1950s. Only fishers who have been members for more than two years are allowed to fish in the best fishing ground around the Yamari Island. The rules were revised in 1975, allowing fishers who have been members for one to three years to fish within the fair fishing grounds. Only those who have been members for five and seven years are allowed to fish within good fishing grounds. Fishers who have been members for eight years or longer are allowed to fish in the excellent fishing ground around the Yamari Island. Those fishers who have been entitled to fish in the excellent fishing ground for more than four years receive a 100% share from the pool account. In 1984, the rules were relaxed so that fishers who have been members for the first six years can harvest lobsters in all fishing grounds except the excellent ones. Those who have been members for seven or more years can now fish in the excellent fishing ground with a 100% share from the pool account system.

Unlike the Nomaike FCA, whose management success is based on the fishers' behaviors, compliance behavior, conflict avoidance, and culture values, the Katsuura FCA' success is attributed to the pool account system. Under the pool account system profits are equally shared among the fishers. The equal profit scheme consequently reduces competition among the fishers in the lobster fishery, where, prior to the introduction of the pool account system, the fishery was overwhelmed by high competition, especially on the very productive fishing grounds.

By their nature, lobsters normally do not migrate and are relatively immobile. Accordingly, fishing boats aggregate and crowd particular fishing grounds that are the most productive. The stock is then easily overfished. Other fishing regulations adopted by the fishers, such as closed seasons, closed areas, limiting mesh size and numbers of gill nets, and minimum catch size, were not enough to reduce competition among the fishers. The pool account system effectively solved the problem. Once all the fishers started getting an equal share, there was no reason for them to compete. This turned out to be beneficial for the sustainability of the stock as well.

Less Successful FCAs

Despite being known as the oldest and the most successful co-management systems in the world (Lim, Matsuda, and Shigemi, 1995; Weinstein, 2000), some of the Japanese FCAs have experienced problems and conflicts among their members. The most outstanding problems and conflict among members are from seven FCAs studied by

Matsuda and Kaneda (1992). All the fisheries in these FCAs harvest highly variable species such as sardine, mackerel, and squid. Most of the conflicts among the fishers are about fishing gear and territory. Some were able to resolve the conflicts by specifying fishing area with regard to the type of fishing gear and by clearly specifying fishing rights granted to the fishers in each prefecture within the same FCAs. These FCAs are the Kyūroku-tō island, the Ariake sea, the Suō-Nada, and Hachinohe, and the Tone Estuary. The fisheries in kyūroku-tō island are for mackerel and abalone, while the Ariake fishery is shellfish farming and the Hachinohe fishing is for squid and mackerel and the Tone Estuary fisheries are for mackerel. Matsuda and Kaneda did not specify the type of fishery for the Suō-Nada.

The first two FCAs have boundary conflicts between two prefectures. The problem in the Suō-Nada is conflict among three prefectures that have different interests in fishing and socio-economic backgrounds. The conflict in the Hachinohe and the Tone Estuary is a gear conflict between purse seine fishers and fishers angling for mackerel. Clarifying fishing rights, including specifying fishing areas for the prefectures, have settled the conflicts in all four cases.

However, some of the seven FCAs experienced long-term conflicts among their fishers, in spite of attempts to specify fishing rights. These FCAs are the Sukuma Bay and the Hachinohe. Because of greater availability of information and the prospect of evidence that fish stock characteristics may influence fishers' cooperation, I provide more details for these two cases than I have done on the first four cases. One FCA conflict that I will not describe in detail is the Essa Strait. This case of conflict, which differs from the other six cases in the seriousness of the conflicts between trawl fishers and the fishers who use traditional gear such as angling and long line, has never been solved. In addition, Matsuda and Kaneda provide no information on the fish species involved and there are not enough details to pinpoint evidence of the influence of biological parameters on fishers' cooperation.

The Sukuma Bay FCA. The outstanding fishery in this area is for sardine, which is shared between the Ehime and Kōchi prefectures. Incidents between the two prefectures date back to the Edo Period. The conflict became more serious and occurred more often after the transfer of fishing rights for four islands in the bay from the Kōchi prefecture to the Ehime prefecture in 1971. As a result, the Ehime fishers had to obtain fishing licenses to fish in the Bay and the arrangement of fees for fishing became a problem between the two prefectures. The license basically specifies the fishing area in which the Ehime fishers are allowed to fish. The persistent conflict was made worse by the introduction of purse seine fishing for sardine and the use of trawls by the Ehime fishers, while the Kōchi fishers still used traditional fishing gear, such as angling, long line and set net.

There were several attempts to resolve the conflict, including several agreements on the terms of fishing. Following each agreement a new incident occurred of illegal fishing by the Ehime fishers in prohibited areas. Most of those agreements were aimed at adjusting and redefining the fishing rights, especially the right for fishing territory. Finally, a more effective agreement was reached in 1969, which resulted in fewer problems during 1969 to 1977. Several reasons underlay this effective agreement: (1) an administrative effort by both prefectures to improve monitoring by increasing the number of coast guard boats and by promoting enforcement education among fishers; (2) a shift of the purse seine fishing ground from Sukuma Bay to Ehime waters, following ecological changes; (3) a change from a rate wage to a fixed rate; and (4) good communication on license renewal. However, the Ehime fishers illegally fished again in 1977. In 1978 the Ehime fishers canceled all their fishing rights.

The Hachinohe FCA. The problem in the Hachinohe FCA has been described as the squid-mackerel incident. The problem is conflict between squid anglers and mackerel purse seiners. An agreement was reached in 1966 with the introduction of a restricted area and season for purse seine. In 1968, the squid landings started decreasing. The decline of squid drove the price higher, which encouraged seiners to illegally fish for squid and caused a new conflict between the anglers and purse seiners. The conflict was solved in 1969 with an agreement to increase flexibility on the restricted fishing area and to allow only local purse seiners to fish from November 16 to December 31.

The last conflict between the two parties took place in 1970 because of higher competition on the same fishing ground and the illegal fishing for squid by the purse seiners. Revision of the last agreement focused on the issue of distance between vessel and gear operations, adjustments on production, and prevention of illegal fishing of squid. Since the last agreement, few conflicts have been reported.

Comparison of the More and the Less Successful FCAs

When comparing the more and less successful Japanese FCAs, the most striking difference between the two groups is whether they have flexible and adjustable regulations. Most of the successful cases actually adjust their management regulations in response to the biology of fish stocks so as to promote stock sustainability. An example of an FCA that has adjustable and flexible regulations is the Katsuura FCA, a lobster fishery. Because lobsters do not migrate and are sedentary species, they are easily caught and can be overexploited in a short period of time. Catch per unit effort for lobster at the beginning of the season is much higher than later in the season (Katsuura Fishermen's Cooperative Association, 1992; Wilson, 1994). As the fishing continues, the stock rapidly and drastically declines. The fishers who happen to locate a good spot ahead of the others will have more of a chance to make a good catch. Consequently, there is high competition even during bad weather that causes accidents. Limited entry and the profit-sharing pool accounting system are the two main management measures that the Katsuura FCA adopts and adjusts in an attempt to reduce the problems of competition among members and overfishing.

Unlike limited entry programs in many fisheries that attempt to control fishing effort by limiting the numbers of fishers, boats, or fishing gear (Sissenwine and Kirkley, 1982; Anderson, 1994; Wilson, 1994), the Katsuura FCA's limited entry program specifies details about the fishing grounds and which fishers can fish on each fishing ground. The lobster fishers established three classes of fishing grounds: fair; good; and excellent fishing grounds, each of which is subjected to different levels of restrictive access. Only the fishers who have been members for more than seven years can fish in the excellent fishing grounds. Those who have been members for five to seven years can fish anywhere except the excellent fishing grounds.

In addition to limited entry, the profit-sharing pool accounting system helps promote successful management by increasing fairness among the members. The fishers get their shares equitably. The profit-sharing pool accounting system is normally applied in the excellent and good fishing grounds for a certain period. The adjustment to the profit-sharing system conforms to the nature of lobsters. The excellent and good fishing grounds are opened for a short period of time and the lobsters are fished down until their abundance is the same as in other fishing grounds. Once all the fishing grounds have about the same lobster abundance, all the fishers have equal rights to fish where they want. After all fishing grounds are opened for everyone, some fishers leave the lobster fishery for other fisheries because lobster fishing is their part time job. In this manner, competition, especially in the excellent fishing grounds, and excessive fishing effort are reduced. The adjusted limited entry program serves the lobster fishery as a management tool in conserving the stock, while the profit-sharing pool accounting system serves the fishery as a management tool that brings equity to the system.

In contrast to the more successful FCAs, regulations in the less successful FCAs are based solidly on territorial fishing rights. The characteristics and nature of fish stocks were not taken into consideration as a rationale for adjusting the management programs. Despite the fact that both of the less successful cases, the Sukuma Bay FCA and the Hachinohe FCA, had well-specified fishing areas and fishing rights, conflict among the fishers and illegal fishing still existed. In addition, as mentioned by Lim, Matsuda, and Shigemi (1995), the Japanese place high cultural value on compliance and conflict avoidance. The fishers in the less successful FCAs should not differ in their cultural values from the fishers in the other successful FCAs. Well-specified fishing rights and compliance and conflict avoidance behaviors are two of the key factors to successful co-management, which the Sukuma Bay FCA and the Hachinohe FCA did not appear to lack. There should be some driving factor that provides an incentive for the fishers to illegally fish. The fishers might see the high variability of stocks, such as squid, sardine, and mackerel, as an excuse for illegal fishing. Declines in the population of small pelagic shoals like sardine and mackerel are hard to blame on overfishing because these stocks are susceptible to environmental changes (Csirke, 1988). Another source of variability in fish stocks that has been widely discussed is variability in recruitment, which is known to be the main source of uncertainty in fisheries management (Sissenwine, 1984b). It has been recognized that abundant pelagic species fluctuate over time due to high mortality during the larval stage. Therefore, fluctuation and depletion of fish stocks appears to result from natural causes rather than fishing (Bakun and Csirke, 1988; Sissenwine, 1984b; Wilson, 1994). The fishers may realize this about the nature of the stocks and take a chance on being caught, while fishing illegally.

In principle, limited entry or license limitation aims to control fishing effort so that the harvest and growth are balanced and the harvest is sustainable (Anderson, 1994; Gimbel, 1994; Sissenwine and Kirkley, 1982; Wilson, 1994). The primary concern of limited entry is economic efficiency in allocating resources because of its potential for dealing with the problems of open access fisheries, dissipating economic rent and overfishing. Because no individuals own common pool resources, they can exploit the resources as much as they want (Hardin, 1968). Economically, the individuals continue to exploit the resource until economic rent is dissipated and the profit from exploiting becomes zero. Limited entry controls fishing effort by limiting the number of fishers, boats, or fishing gear. Therefore, it prevents the build up of excess fishing effort, which dissipates economic rent. Consequently, limited entry contributes a side benefit of preventing overexploitation of the resources.

Despite its advantage for fisheries management, limited entry has a drawback. Practically, it is very difficult to control fishing effort because limiting the numbers of boats, fishing gear, or fishers does not control fishing effort if the fishers can increase their efficiency. Limited entry alone encourages fishers to invest in higher efficiency boats and gear, which also increases fishing costs (Scott, 1989). Moreover, by limiting the numbers of fishers, fisheries managers need to make serious decisions regarding who should be allowed to participate in the fisheries. Excluding some fishers accordingly initiates social problems. The fishers who are excluded feel unfairly treated by being denied the opportunity to gain benefits from the resources. In particular, fishers whose families have been fishing for generations would not prefer limited entry, especially if the fishery is labor intensive (Kahn, 1995). These fishers are unlikely to be profit maximizers. They have concerns that take precedence over maximizing profits, such as maximizing income, the desire to maintain their families' traditional fishing career and receiving fair treatment from fishing organizations. The fishers may be concerned about their incomes rather than the profits that they potentially gain from fishing. Being able to participate in fishing activities is also important to the fishers, especially those fishers whose families have a long histories of fishing that have been passed on for generations. Additionally, the fishers may feel unfairly treated by being denied the opportunity to gain benefits from the resource that they consider belongs to them. The down side of limited entry is entirely unacceptable and causes conflict in fishing societies.

A good example is the incidence of illegal fishing in the Hachinohe FCA. The mackerel fishers who illegally fished for squid may have felt they were unfairly excluded. With the attraction of high squid price and higher efficiency fishing gear, their opportunistic behavior emerged. A compromise was reached when the authorities put less restrictions on the fishing area and allowed the local purse seines to fish in some areas.

Another interesting piece of evidence is the problem of declining membership in the successful Nomaike FCA. The number of members in Nomaike has been declining through time (Lim, Matsuda, and Shigemi , 1995). Rather than attempt to find successors, the fishers encourage their children to get other jobs because they can foresee the uncertainty in the fishing business as the fish stocks continue to decline. This evidence shows that the biological characteristics of the fish stocks influence the fishers' decision to join the cooperatives. The Nomaike FCA is not the only FCA that has faced the problem of a lack of successors. Other FCAs, such as FCAs in Mugi city, Sukuma Bay of Shizuoka prefecture, have also faced the same problem.

GAME THEORY

DEFINITION

Game theory has been applied to the study of conflicts that arise in many fields including management science. The main and original development was for the study of conflict behavior in economics. Game theory uses mathematics to describe strategic behavior arising from conflicts among individuals (Luce and Raiffa, 1957; Rapoport, 1974; Rasmusen, 1989; Mesterton-Gibbons, 1992). It also proposes solutions for such conflicts. Strategic behavior refers to decision-making actions by an individual that reflect not only the individual's preferences to alternative choices but also to the anticipated decisions of other individuals. An individual's decisions affect the decisions of others. A conflict in game theory generally has four elements: (1) a set of individuals or decision makers, called players; (2) a set of strategies available to each player, which describe how players can play the game from start to finish; (3) a set of outcomes, each of which is the result of particular strategic choices made by the players during a given play of the game; and (4) a set of payoffs accorded to each player for each of the possible outcomes.

Game theory analysis has two main components, a description and a solution of a game (Shubik, 1982). The description of a game explains in mathematical terms the type of game and its rules. It incorporates all aspects of the game into a mathematical model. The solution is related to the outcome of a game, which is a combination of the players' best strategies.

BACKGROUND

Von Neumann first developed game theory, originally called the mathematical theory of games of strategy, in many phases in 1928 and 1940-1941 (Von Neumann and Morgenstern, 1964). The purpose was to understand and describe interactive decision making in economics. In a strategic situation, an individual's decision does not depend solely on his own preference, but also on the anticipated decisions of other individuals. For example, a buyer and a seller negotiate a reasonable price by reacting to each other's responses. However, this interactive behavior, an important economic factor, is very difficult to analyze and is not easily measured. This difficulty might lead one to believe that mathematics should not be used in studying economic phenomena. However, Von Neumann and Morgenstern argued that the failure of mathematics in economics was mainly due to unclear specification of the problems, which consequently made the mathematics difficult and nonsensical. They developed game theory as a mathematical tool to understand interactive behavior in a market situation.

Generally, the basic application of game theory is to find out what might happen given the assumption that players try to maximize their payoffs (Rasmusen, 1989). Game theorists construct a game by assigning payoffs, strategy sets, and rules for the game. They then find an equilibrium solution and the outcome of the game. The solution is a strategy profile that suggests what the players will do or what strategies the players should pick in order to maximize their payoffs. The outcome of the game consists of a set of elements associated with the equilibrium solution. The game theorist might be interested in the set of payoffs or any of the values consequently obtained from the players' actions or choices that the players make.

CLASSIFICATION OF GAMES

Game classification schema are dependent upon the questions of interest to the classifier. Different questions of the same game may require a different classification schema.

A traditional game classification is cooperative versus non-cooperative (Mesterton-Gibbons, 1992). This classification is based upon whether players in a game can communicate with each other or commit to promoting joint benefits, in which case the game is said to be cooperative (Schotter and Schwödiauer, 1980; Shubik, 1982; Rasmusen, 1989). On the other hand, a game is said to be non-cooperative if the players cannot communicate or make binding agreements.

Games can also be classified by the number of the players in a game (Rapoport, 1974). For example, a game with two players is called a 2-person game. An n-person game is one in which the number of the players is n.

Another important aspect of game theory is information, such as what players know about each other and the structure of the game. If the game encompasses more than one move, players have the opportunity to observe and gain information about the other players. The information can then be used to make decisions. In this environment, information becomes important to the players. The type and amount of information varies. Accordingly, game theorists classify games based upon the structure and details of the information available: extensive form versus strategic (or normal) form (Mesterton-Gibbons, 1992; Rasmusen, 1989, Shubik, 1982).

The extensive form game is concerned with the details of the information, i.e. the sequence of moves (when and who can move), what the players know about the game, the restrictions on specific moves, states of the game, and all possible information for each state. Examples of extensive form games are board games like checkers and backgammon where the rules of the game specify the sequence of moves, possible moves for each state of the game, and the conditions for when the game ends.

In the strategic form the focus is on calculating all possible strategies of the game and the corresponding payoffs to each strategy, other details are omitted (Shubik, 1982; Rasmusen, 1989). The game is reduced to a payoff matrix.

GAME THEORY AND FISHERIES MANAGEMENT

The theory of games has been applied as a tool for modeling conflict situations in various fields, but mainly in economics. However, in recent years game theory has increasingly played an important role in other fields including political science, social science, and operations research (Shubik, 1982). It also has been applied extensively in the management sciences, such as the management of common pool resources.

In the field of common pool resources there have been many studies that have attempted to describe participants' behavior in cooperative organizations in the context of game theory (Ostrom, 1990). Most of the studies have viewed the problem of cooperative behavior in the context of the prisoner's dilemma, the decision-making process of two prisoners who balance options and pay-offs. For instance, Axelrod (1980) investigates the conditions under which cooperation will emerge in a world of egoists without central authority. He employs the iterated prisoner's dilemma to analyze how an individual who is pursuing his/her own interest will act towards common resources. In his analysis, he allows only two individuals to interact with each other at a time. He concludes that cooperation could emerge if an individual sees that he/she will have to interact with others in the future.

In fisheries management game theory has been applied particularly in the study of transboundary fishery resources. The expansion of Exclusive Economic Zones (EEZ) in the mid 1970s gave rise to joint ownership of fisheries resources for those fish stocks that straddle the EEZ boundaries of two or more nations. An example is the joint ownership of the cod stock between Iceland and the United Kingdom (Munro, G. 1979; Levhari and Mirman 1980). Economists and applied mathematicians have studied and analyzed joint ownership situations to look for solutions to these kinds of conflicts (Munro, 1990). The analyses are commonly approached in the framework of a bioeconomic fishery model in addition to concepts applied from game theory. For example, Levhari and Mirman (1980) applied differential game theory to analyze the interaction between two countries that exploit a common a fish stock. Differential game theory is a branch of game theory that links control theory and game theory (Shubik, 1982). Control theory deals with the dynamic behavior of a system in a continuous time framework. In the study of Levhari and Mirman (1980) the dynamic system is the fish stock, while the strategic aspect is the interaction between the two countries who compete for the fish. They solved for the strategic behavior of the two countries using the concept of the Cournot-Nash equilibrium, which for their model means that each country selects its harvest rate so that it maximizes the present value of the flow of future profits. Levhari and Mirman concluded that the solution for the conflict in the non-cooperative game, where the two counties do not communicate, resulted in stock extinction. In contrast, they found that under a cooperative game setting, where the two countries communicate and make binding agreements on cooperation, the stock is likely to thrive.

Lewis and Cowens (1982) applied the theory of repeated games (or supergames) to investigate the sustainability of cooperative arrangements among fishers. A supergame is a class of dynamic game that changes sequentially over time. The supergame focuses on infinitely repeated plays of the same game, i.e., the players make the same decision repeatedly in the same situation (Rasmusen, 1989; Shubik, 1982). In addition, an action in the repeated game is independent of the previous actions of any player. The model developed by Lewis and Cowens differs from the standard repeated game at this point.

The previous actions of players (fishers) affect the fish stock, which in turn affects the current decisions of the players. From their study, Lewis and Cowens found that when the number of fishers increases, the incentive for individuals to cooperate increases. In addition, they showed that the scarcer the resources, the higher the degree of cooperation among the players.

Munro (1990) applied a bioeconomic model of a fishery, together with game theory, in an investigation of conflicts arising from management of a transboundary resource. The fishery model was based upon the Schaefer model for the biological productivity of the fish stock. The game aspect to the model was two countries who had joint ownership of the fish stock. Each country attempts to harvest the stock to maximize profits, but because the two countries share the fish stock, harvesting by one influences how the other decides to control its own harvest. The strategic interaction can be described mathematically as a game. Munro then set the strategic interaction between the two countries in the framework of a non-cooperative game and a cooperative game. He found that in the non-cooperative setting, the two countries do not communicate and suffer worse economic consequences compared to those experienced under the cooperative setting.

III. METHODS: ANALYICAL FRAMEWORK

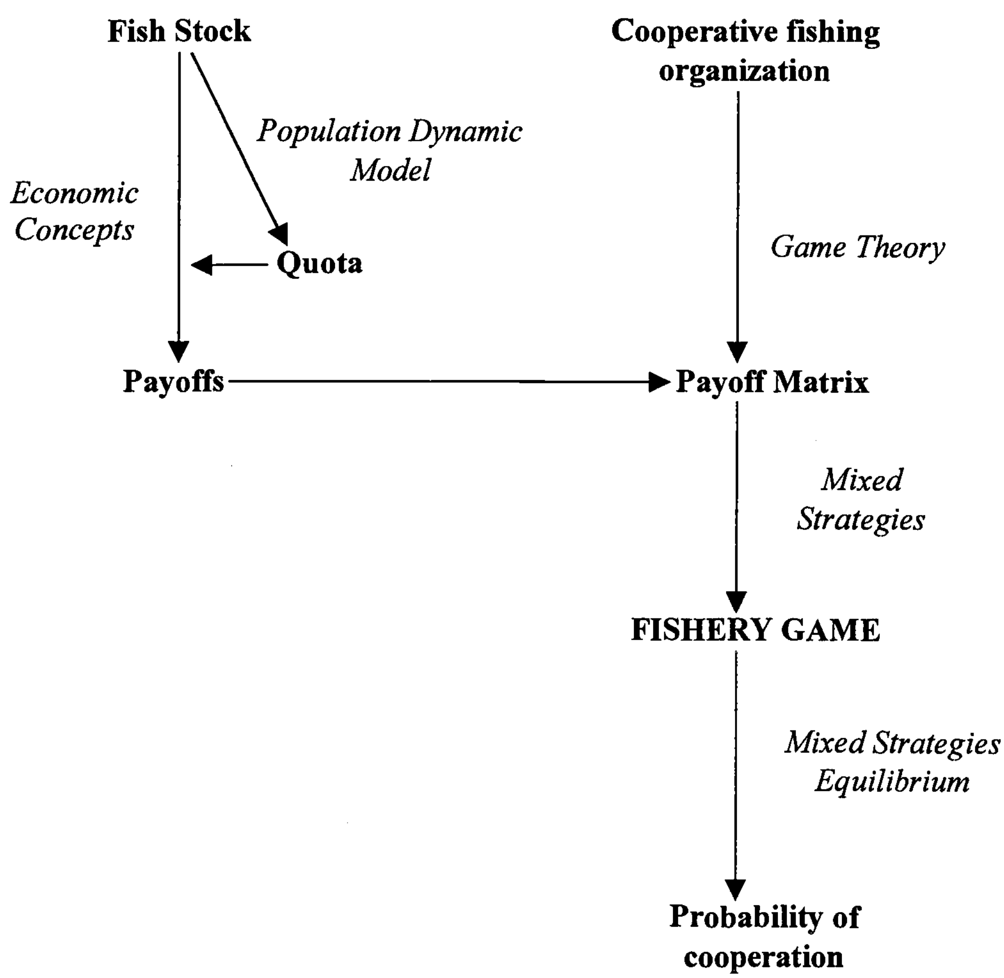
I will apply game theory to explore the stability of cooperative behavior in a cooperative fishing organization in which the members are granted shares of an annual harvest quota. Figure 1 shows the general analytical framework. I use economic concepts and population dynamics models to assign the payoffs that are the basic elements for the game. I apply game theory to capture the strategic situation arising from the different payoffs and perceptions about the fish resources. The strategic situation can be described in terms of a decision matrix, which I call the "fishery game". Then, I introduce the concept of mixed strategies and apply it to the fishery game in order to solve for the equilibrium outcomes of the game. In this section, I first explain details of the framework of the fishery game. Subsequently, I explain all the crucial concepts applied in developing the fishery game.

THE FRAMEWORK OF THE FISHERY GAME

The aim of this analysis is to investigate whether certain biological characteristics of a fish stock have an influence on the fishers' decision to cooperate and catch only their agreed shares of a harvest quota. The biological characteristics for the fish stock are modeled using two parameters, the intrinsic growth rate (r) and the stock size. If a fish stock has a high value of r it implies that the stock grows fast and I assume that it is also likely to be highly productive and variable (Gulland, 1983; Myers, et al, 1997). The fishers may decide to cooperate or not based on the biological status of the fish stock.

For simplicity, I assume the two fishers are members of a fishing cooperative organization that grants its members shares of an annual harvest quota. I assume further that both fishers are homogeneous in their fishing operations—operating with the same size fishing boat and the same type of fishing gear and thus having identical fishing power. Also, the two fishers have similar fishing costs and experience the same market price. In contrast to studies that applied differential games to analyze cooperation in a fishery, I analyze the strategic situation in a discrete time framework.

Figure 1. Analytical Framework for the Fishery Game



There are two kinds of interactions and reactions among the organization's members. I start with the premise that the two fishers, who initially are members of the cooperative organization, are willing to cooperate and limit their harvest to their allocated portion of the harvest quota. Otherwise, they would never have joined the organization. I then assume that during the fishing season the fishers are unsure about the condition of the fish stock and whether other fishers will continue to cooperate. They may decide to cheat and catch more than their share of the harvest quota.

After applying game theory to a model for biomass and fishery dynamics to mimic all crucial components for the fishery game, I solve for the equilibrium outcome of the game. The outcome of the game in this analysis is the probability that both fishers continue to cooperate and catch only their own shares of the harvest quota. I then analyze how the biological factors in the game influence the fishers' decision to cooperate. When the fishers are all cooperative they harvest only the shares allocated to them by the organization. So, the share for each fisher is the total quota divided by the number of fishers.

Despite their homogeneity and commitment to the fishing cooperative, the fishers differ in their perceptions about the fish stock and in their attitudes toward risk, which results in different tendencies to cooperate. From an economic perspective, risk aversion refers to a person who prefers less variable rewards (Pindyck and Rubinfeld, 1992). Someone who is risk averse prefers a reward with high certainty to one with less certainty, even though the reward is less valuable. In contrast, a risk-prone person prefers highly valuable rewards despite high variability of the rewards. For example, a risk averse person would rather invest his money in a saving account than in the stock market because he can gain a more certain rate of return from the bank, even though with a lower rate when compared to the gain from the stock market. A risk prone person will rather do the opposite. Accordingly, the two fishers have different perceptions of and reactions to potential change in the fish stock. The fisher who is risk adverse would want to fish in a conservative manner so as to ensure that the stock will be productive through time. Meanwhile, the fisher who is risk prone would be willing to gamble on future productivity and harvest as much as possible at the present. Additionally, if the stock has large intrinsic growth rate (r), the risk prone fisher might perceive that the stock, by its nature, is fast growing, so that the stock is highly productive and would rapidly recover from any overharvesting. These fishers might be willing to gamble that the stock growth is sufficiently fast that they could catch more than their share and nobody would know it. Because the stock grows fast, their overharvesting would not result in any apparent depletion of the stock in the future.

Both fishers know each other's attitudes towards risk. During the fishing season, both fishers are unsure about each other's decision regarding the harvest. The fishers may communicate, but in practice, they will not tell anybody if they decide to cheat and catch more than their portion of the harvest quota. Therefore, it is more reasonable to assume that communication does not take place. As a consequence, the commitment to cooperate may not be adhered to. Without communication and commitment the fishery game cannot be considered a cooperative game. Solution concepts other than the bargaining concept used in cooperative games need to be introduced to solve the fishery game.

Because one fisher does not know whether the other will continue to cooperate or not, the fishers do not know each other's payoffs. To solve for the equilibrium outcome of the game, given that the players' payoffs are unknown, I need to incorporate mixed strategies into the game. The mixed strategy approach applies probability distributions over each player's pure strategies so that all possible payoffs can be calculated for each player corresponding to the strategies that the players would select. With the possible payoffs, the game is then solvable.

MIXED STRATEGIES

A mixed strategy is a probability distribution assigned to the set of pure strategies for a player. For example, if a player has a set of pure strategies that has two elements, {cooperative, non-cooperative}, a mixed strategy over this pure strategy set would be {pr(cooperative, 1-pr(cooperative) }. Basically, the mixed strategy indicates the likelihood that the player will play each pure strategy. The mixed strategy of {0.3, 0.7} means that in repeated trials of the game the player is likely to play the cooperative strategy with a probability of 0.3 and to play the non-cooperative strategy with a probability of 0.7. The outcome of the game is the payoff combination from each player corresponding to the mixed strategies equilibrium. The mixed strategies equilibrium is the mixed strategies combination selected by the two players. It should be noted that the payoffs in the mixed strategies are average values averaged over a large number of trials of the game, whereas the payoffs obtained from a game with a pure strategy equilibrium are certain. The pure strategy equilibrium refers to the combination of the pure strategies selected by the players that result in the maximum payoffs for all players.

Mixed strategies are usually applied to induce an equilibrium solution in a game that has no pure strategy equilibrium (Luce and Raiffa, 1957; Dresher, 1961; Rasmusen, 1989; Gibbons, 1992). By applying a mixed strategy to a game, we basically expand the strategy set of a player. By incorporating a probability distribution over the set of pure strategies, the payoffs corresponding to each pure strategy can consequently be regarded as expectations, which are continuous. Hence, the payoffs are expanded for each pure strategy according to the mixing probability. In this manner, when one player pursues a mixed strategy, the other player will always find a mixed strategy that will be his/her best response. An equilibrium finally exists in the game.

Even though the mixed strategies concept is usually focused on games that have no pure strategy equilibrium, it can also be applied to games with pure strategy equilibria. Regardless of the presence of a pure strategy equilibrium, a player may have reasons to play strategies other than the strategy that produces the equilibrium. In particular, the player may decide to deviate from the equilibrium strategy if he/she feels that his/her opponent might also deviate from the equilibrium strategy. From the player's point of view, mixed strategies provide a better defense against his/her opponent. When one player plays a pure strategy randomly, his/her payoff function will be unpredictable for his/her opponents and it will be hard for the opponent to respond in such a way that the outcome of the game is in the opponent's favor. For example, suppose a pitcher in a baseball game has two choices for throwing a ball, fast ball or curve ball. If the pitcher chooses to play each strategy randomly, it will be hard for his/her opponent to anticipate the pitches and choose the best swing to counter the pitcher's mixed pitches.

EQUILIBRIUM IN MIXED STRATEGIES

Underlying the concept of an equilibrium in mixed strategies is the idea that the players try to hide their selected strategy from each other. When a game does not have a pure strategy equilibrium none of available strategies is uniquely best for all the players. The best that a player could do is to anticipate what strategy his opponent will select or to hide his strategy from his opponent. Von Neumann and Morgenstern (1964) suggest that the rational way for a player to hide his strategy is to play equal odds for all strategies. Once the player decides to play each strategy with equal chance, no matter which strategy his opponent selects, the player's probability of winning or losing will be the same. Also, his expected payoffs from playing the two strategies are the same. This concept has been applied as a rule for finding an equilibrium in a game with mixed strategies--a player should be indifferent to the available strategies. In practice, one assumes that a player expects that his opponent will try to hide his strategy by playing each option with equal odds. The player then tries to figure out what strategy he can choose as the best response to his opponent's random play. The first thing that the player would do is to assign a probability distribution over the opponent's strategy set. He then equates all possible payoffs from the strategies of the opponent.

Consider, for example, the matrix game illustrated in Table 1. In the first column are the pure strategies available to player A, while in the first row are the pure strategies available to player B. The numbers in the parentheses in each cell represent the payoff combinations corresponding to the strategies selected by both players. The first number in each set of parentheses is the payoff for player A, while the second one is the payoff for player B. For example, the payoff combination (-1, 3) represents the payoff of –1 for player A when he plays the cooperative strategy, and the payoff of 3 for player B when he plays the non-cooperative strategy. Notice that neither player has a best response to his opponent. Neither player will knowingly choose the strategy combination (non-cooperative, non-cooperative) because it yields zero payoffs for both players. Also, neither player would prefer the strategy combination (non-cooperative, cooperative) because it would not give the players the highest payoffs. Player A would prefer the cooperative strategy provided player B also chose the cooperative strategy because it gives A the highest payoff. Likewise, player B would prefer the non-cooperative strategy when player A chose the cooperative strategy. Both players cannot simultaneously have their best payoff from the strategy preferred by their opponent. The game has no pure strategy equilibrium.

Table 1. A matrix game that has no equilibrium solution

		Player B	
		Cooperative	Non-Cooperative
Player A	Cooperative	(3, 2)	(-1, 3)
	Non-cooperative	(-1, 1)	(0, 0)

We can induce an equilibrium by assuming that each player assigns probability distributions to his opponent's strategy set. Suppose that player A chooses cooperative and non-cooperative strategies with probability p_A and $1-p_A$ respectively (Table 2).

Fisher B chooses cooperative and non-cooperative strategies with probability of p_B and $1-p_B$ respectively. The expected payoffs for A are:

$$\pi_A (p_A = 1, p_B) = (p_B)*(3) + (1-p_B)*(-1) = 4p_B-1 \qquad (5)$$

$$\pi_A (p_A = 0, p_B) = (p_B)*(-1) + (1-p_B)*(0) = -p_B \qquad (6)$$

At the mixed strategy equilibrium fisher A is indifferent between the expected payoffs from his choice of strategy. Therefore, setting equation (5) equal to equation (6) we get

$$4p_B-1 = -p_B;$$

$$\therefore p_B = 1/5$$

Table 2. Introducing probability distributions

		Player B		
		Cooperative	Non-Cooperative	
Player A	Cooperative	(3, 2)	(-1, 3)	p_A
	Non-cooperative	(-1, 1)	(0, 0)	$1-p_A$
		p_B	$1-p_B$	

Likewise, the expected payoffs for fisher B are:

$$\pi_B (p_A, p_B = 1) = (2)*(p_A) + (1)*(1-p_A) = p_A+1 \qquad (7)$$

$$\pi_B (p_A, p_B = 0) = (3)*(p_A) + (0)*(1-p_A) = 3p_A. \qquad (8)$$

$$p_A+1 = 3p_A;$$

$$\therefore p_A = 1/2$$

Therefore, the mixed strategy equilibrium outcome is (p_A=1/2, p_B=1/5) implying a 50% chance that fisher A will be cooperative and a 20% chance that fisher B will be cooperative. One might be interested in the equilibrium payoffs. From these probabilities that produce the mixed strategy equilibrium we could calculate the equilibrium payoffs by substituting p_A and p_B in equations (5) and (7) or (6) and (8), which yields the payoff combination (1.5, -0.2)

GENERAL INTERPRETATION OF MIXED STRATEGIES

The meaning of mixed strategies depends on how one interprets the probability distribution (Luce and Raiffa, 1957). In general, a mixed strategy defines the likelihood that a player would play each pure strategy in a pure strategy set. For example, a mixed strategy of {0.3, 0.7} for a player that has two pure strategies {cooperative and non-cooperative} suggests that the player would play the cooperative strategy with probability of 0.3 and the non-cooperative strategy with probability of 0.7.

More specifically, we can view a mixed strategy as measuring one player's uncertainty about what the other players will do (Gibbons, 1992; Brandenburger, 1992). Suppose a game with players A and B has a pure strategy set of {cooperative, non-cooperative}. The mixed strategy {0.3, 0.7} for player A implies that player B believes that player A would play the cooperative and non-cooperative strategy with probability 0.3 and 0.7 respectively. Given this belief, player B needs to find his/her mixed strategy that is the best response to player A's mixed strategy.

PROBLEMS IN INTERPRETING MIXED STRATEGIES

Most modelers and economists generally avoid applying mixed strategies to their models (Luce and Raiffa, 1957; Rasmusen, 1989; and Brandenburger, 1992). Interpreting mixed strategies is always problematic. It contradicts the fact that human players in a game naturally have no strict incentive to act randomly, nor do they normally randomize when making decisions. Moreover, mixed strategy equilibria are unstable, because even if one player uses an equilibrium strategy it is unnecessary for their opponent to respond with an equilibrium strategy.

Despite these problems of interpretation, the mixed strategies approach is a useful tool because of its applicability to certain situations where other types of solutions cannot be found. Examples are the situations where there is no pure strategy equilibrium for the game and where all players do not know what strategies their opponents will play. The mixed strategy approach can introduce an equilibrium for games having no pure strategy equilibrium

To find an equilibrium of a game, game theorists need to classify the type of the game. Consequently, game theorists apply a solution concept according to the type of game to solve for the equilibrium, for example, applying the bargaining concept to find an equilibrium of a cooperative game. For a pure strategy game where an equilibrium of the game is possible to find, we focus on the players' communications. Depending on whether the players are allowed to communicate with one another, a game can be classified as either a cooperative or non-cooperative game. As opposed to a non-cooperative game, in which the players are not allowed to communicate, a cooperative game is a game where the players are allowed to communicate and make binding agreements. However, a game may be classified neither as a cooperative nor a non-cooperative game with regard to some situations underlying the game. An example is the fishery game, in which the players do not know their opponents' strategies and also do not communicate with one another. Mixed strategies can be applied to solve for an equilibrium of the game.

BIOMASS DYNAMIC MODEL

The biomass dynamics model describes the biomass of a fish population at the end of a time period in terms of the biomass of the stock at the start of the time period, the natural growth rate of the stock, and the harvest. The basic logistic growth model is used to describe the growth increment in stock biomass, and the harvest or catch is assumed to be proportional to effort and the initial stock size (Hilborn and Walters, 1992; King, 1995). Mathematically, the basic biomass dynamics model is described as follows:

$$B_{t+1} = B_t + r * B_t * \left(1 - \frac{B_t}{K}\right) - H \tag{1}$$

Where B_t is the stock biomass at the start of interval t, K is the carrying capacity, r is intrinsic growth rate, and H is total harvest during the time interval.

In this discrete time modeling framework the harvest is given by the standard catch equation of fisheries (Gulland, 1983):

$$H = B * \frac{F}{F + M} * \left[1 - \exp(-(F + M) * t)\right] \tag{2}$$

where B is biomass at the beginning of the time period, F is the fishing mortality coefficient, M is the natural mortality coefficient, t is the time interval, which is one fishing season in this analysis.

Because the fishing season is short, I assume that natural mortality during the fishing season is negligible compared to fishing mortality. The harvest equation simplifies to:

$$H = B * [1 - \exp(-F)], \tag{3}$$

I make the standard assumption that the instantaneous rate of fishing mortality is proportional to the amount of fishing effort,

$$F = q * f \tag{4}$$

where f is fishing effort, and q is the catchability coefficient. In this model fishing effort measures the amount of fishing gear applied during the fishing operation. Therefore, the harvest equation for this analysis is:

$$H = B * [1 - \exp(-q * f)] \tag{5}$$

ECONOMIC MODEL

The economic components of the model are the revenues and costs produced by fishing,

$$\pi_i = H_i * P - c * f_i \qquad (6)$$

where π_i is profits for fisher i, H_i is the harvest by fisher i, P is market price for fish, and c is cost per unit of fishing effort. As is commonly done in fisheries economics, here I assume that the fish price is constant and independent of the amount harvested and the fishing costs are strictly proportional to the amount of fishing effort.

DISCOUNTING

Economists use the concept of discounting to determine the present value of money or a commodity received in the future. It is normally assumed that a given amount of money or commodity is worth more today than it is worth tomorrow (Hutter, 1996; Prugh, 1995; Pearce and Turner, 1990). Receiving $100 today is worth more than getting it in the future because we can put the $100 in the bank and earn interest.

How much the $100 in the future would be worth today depends on the discount rate, the rate that a future value will be discounted. For example, given a 10% annual discount rate, $100 received one year from today will be worth $90.

If dr is the discount rate then the discount factor is $1/(1+r)^t$, where t is the number of time periods. Economists use the discount factor to convert a future value into its present value using the general formula:

$$PV = FV\left[\frac{1}{(1+dr)^t}\right],$$

where FV is a given future value, dr is the discount rate, and t is the number of time periods. For example, given a 10% discount rate, $1,000 five years from now is worth $620.92 today.

DISCOUNTING & NATURAL RESOURCE AND ENVIRONMENTAL ECONOMICS

Discounting is a concern in natural resource use because it influences the rate of resource use and therefore may affect equity among generations (Lines, 1995; Hutter, 1996; Pearce and Turner, 1990). Discounting can make future generations worse off because the future value of resources is discounted by the present generation. A positive discount rate reflects a higher value of benefits in the present than in the future. Hence, it generates an incentive to the present generation for consuming natural resources now. The higher the discount rate the more rapidly resources will be depleted.

According to Pearce and Turner (1990), there are two reasons why the discount rate is greater than zero, time preference and capital productivity. Time preference is based on the idea that an individual prefers to have benefits now rather than later. Uncertainty about the future strengthens the preference for present benefits. Capital productivity is based on the idea of investing in natural capital. Rather than consuming a natural resource, which is considered as a natural asset, we wait to consume it later. This allows the natural capital to grow so that it can produce more and contribute a higher benefit in the future. In this sense, the future benefit is greater than the present one.

For evaluating natural resources, the choice of discount rate can be controversial. In addition, the decision to assign a particular value for the discount rate is generally influenced by politics. No matter whether the discount rate is high or low there are always supporters and opponents on each side. For example, it is commonly argued that a low discount rate discourages consumption and prevents natural resources from being overexploited. With a low discount rate, it is worthwhile to delay harvest until the resource has had a chance to grow and achieve more of its potential productivity. Therefore, future benefits will outweigh the present benefits. Meanwhile, one could argue that a low discount rate could lead to more business investment and greater use of natural capital, if the interest rate is set in relation to the discount rate (Lines, 1995). At low interest rates it is advantageous to borrow money from the bank for investment. In this manner, more resources will be utilized and, consequently, natural resource depletion and environmental damage are greater. In terms of natural and environmental management, most conservative environmentalists and environmental economists prefer a low discount rate.

DISCOUNTING AND GAME THEORY

Game theorists employ discounting generally with dynamic games, in which players make a sequence of moves, such as in sequential bargaining games (Gibbons, 1992). In the sequential game, which is played in discrete time steps, the players take turns making a bargain at each time period until the game reaches equilibrium, when all players accept each others' offers. It is assumed that players are impatient to have their payoffs now rather than later. As the game goes on, each player's payoff is discounted according to his or her degree of impatience. At the end of a period, the discounted payoffs for the players can be represented as:

$$\pi_P = \delta * \pi_L ,$$

where π_P is the payoff for the present period, π_L is the payoff for the later period, δ is discount factor and $0 < \delta < 1$.

DISCOUNTING AND THE FISHERY GAME

In contrast to the discounting employed in the dynamic game, I apply discounting to represent the fishers' tendencies to cooperate. In the fishery game the fishers have to decide between two strategies, being cooperative and harvesting only their share of the quota versus being non-cooperative and harvesting more than their share. Given that a fisher has a particular tendency to cooperate, it is reasonable that the fisher's tendency to choose a non-cooperative strategy is just

$$\Pr(\text{non-cooperative}) = 1 - \Pr(\text{cooperative}).$$

On a relative scale, if a fisher has a high predisposition to cooperate, then his predisposition to be uncooperative should be low.

Furthermore, it seems reasonable that the fishers tendency to cooperate should be related to the fisher's attitude towards risk and uncertainty about the fish stock, which is characterized in this fishery game by the intrinsic growth rate of the stock (r). I assume that a high value of r implies a more productive and variable fish stock. The productivity and variability of the stock, in turn, will encourage uncooperative fishers to gamble that they could catch more than their shares because the stock would recover rapidly. Also, the fishers may want to catch as much as they can rather than trading the high potential present catch for the uncertain future. In contrast, the cooperative fishers would want to catch conservatively to ensure the sustainability of the highly productive and variable stock.

One would expect that the fishers with a greater tendency to gamble would be less likely to cooperate because these fishers would perceive that their expected cooperative benefits are smaller than the non-cooperative ones. Being cooperative in the context of the fishery game means that fishers catch no more than their quota shares, whereas being non-cooperative means the fishers catch more than their quota shares. When the profits from fishing at the quota are less than the maximum possible profits, there are economic incentives to be non-cooperative. However, because the abundance of a fish stock is uncertain due to environmental changes and variation in the productivity of the fish stock, the stock cannot sustain catches larger than the quota. Catching more than the quota could result in overfishing and stock depletion. Those fishers who are less willing to risk stock depletion would be more cooperative. Meanwhile, those fishers who are more willing to bear the risk would be less cooperative.

My purpose in applying the concept of discounting is not for discounting future profits as normally practiced in economics, but for evaluating fishers' expected benefits given their perceptions and tendencies to cooperate. The factor that I use in evaluating the fishers' profits, given their tendencies to cooperate is

$$\delta_i = \frac{1}{1+b_i * r} \tag{8}$$

where b_i is the risk coefficient for fisher i and r is intrinsic growth rate. I assume that the tendency to cooperate is inversely related to the intrinsic growth rate of the fish stock. The greater the value of δ the higher the tendency for the fisher to cooperate and the lower the tendency to be uncooperative. In contrast, as the value of b_i*r increases, the tendency to cooperate decreases. The term b*r is analogous to the discount rate in standard economics and δ is analogous to the discount factor.

According to Mendelssohn (1981), a fish stock will be fished down to extinction if the discount rate is higher than intrinsic growth rate of the stock. Given the basic assumption in game theory that all players are rational, we should expect that the fishers are rational and would not want to have the stock go extinct. Hence, the discount rate (b*r) must be less than or equal to r, and the maximum value for the risk coefficient b_i is 1. The lowest possible value for b_i is zero—in which case the fishers' discounted cooperative benefit is exactly the same as the undiscounted cooperative benefit and the fishers have the highest tendencies to cooperate.

IV. METHODS: THE FISHERY GAME

I organize this chapter into three sections. The first section describes the problem and defines the form of the fishery game and its elements. The second section sets up the fisheries model and explains in detail the elements of the game, which are the payoffs and the solution. The third section presents the method used to analyze the model. The aim of the analysis is to examine the influence of biological parameters on fishers' cooperation as shown by the outcomes of the game. Specifically, I investigate the general outcomes of the game and then investigate the fishers' cooperation under the mixed strategy outcomes.

PROBLEM SETTING

I assume that two fishers, A and B, are members of a fishing cooperative organization and that a fisheries authority assigns to the cooperative an annual harvest quota. The authority focuses on maintaining sustainable harvests from the fish resource and assigns the quota based upon the fishing rate that will produce the estimated maximum sustainable yield (MSY). The total quota Q is mathematically determined as:

$$Q = r^*B/2 \tag{9}$$

where B is the current stock size, and r is the intrinsic growth rate. Given that the stock grows according to the logistic growth model and that the fishers always catch the quota, the equilibrium stock size will be K/2 and the annual harvest will be $r^*K/4$.

At the formation of the cooperative organization, the two fishers are cooperative and agree to fish up to their assigned quota, which is simply half of the total quota. During a fishing season, one or both of the fishers may deliberately catch more than their quota share and one or both of them may start doubting whether or not the other will remain cooperative and catch only their quota share. Because each fisher's decision appears to depend upon the other's, we can consider the situation a game.

In the context of game theory, when players in a game have to guess the other's decision in order to make their own decision, we can view the game as having the normal form with mixed strategies. The mixed strategy describes the probability that the player would choose a particular strategy. Given a game with two strategies, being cooperative versus being non-cooperative, if fisher A chooses to play mixed strategies it means that he chooses to play each strategy randomly with a certain probability. For example, if fisher A plays mixed strategies by playing the cooperative strategy with a probability of 0.3, then he plays the non-cooperative strategy with a probability of 0.7. In reference to a two-person game, I represent the strategic interaction between the two fishers as a game with the matrix form illustrated in Table 3.

The 2x2-matrix represents the fishery game with two players, fisher A and fisher B, both having two strategies to choose, between cooperative versus non-cooperative. The terms p_A and p_B are the probabilities that fishers A and B will choose the cooperative strategy. The terms π_A and π_B are the payoffs, the profits for fisher A and B. The first subscript denotes the player's strategy, while the second one denotes his opponent's strategy. For example, π_{Anc} is the payoff for fisher A when he plays the non-cooperative strategy, while his opponent, fisher B, plays the cooperative strategy.

Table 3. Matrix for mixed strategies

Fisher B

Fisher A		Cooperative	Non-Cooperative	
	Cooperative	(π_{Acc}, π_{Bcc})	(π_{Acn}, π_{Bnc})	p_A
	Non-cooperative	(π_{Anc}, π_{Bcn})	(π_{Ann}, π_{Bnn})	$1\text{-}p_A$
		p_B	$1\text{-}p_B$	

The payoffs are the actual profits gained from fishing. However, how much the profits from playing each strategy would be worth to the fishers depends on how the fishers value them. I assume that the two fishers value the profits differently depending on their tendencies to cooperate (δ_i), which depend on their attitudes to uncertainty in the fish stock. The benefits realized by player i for deciding to be cooperative are given by

$$\pi_{ic}' = \delta_i \pi_{ic} \tag{10}$$

The realized benefits for deciding to be uncooperative are

$$\pi_{in}' = (1-\delta_i)\pi_{in} \tag{11}$$

For simplicity, in the remainder of this thesis the notation π_{ic} and π_{in} will refer to the realized payoffs for fisher i for playing the cooperative and non-cooperative strategies respectively.

SETTING UP THE FISHERY GAME

In the previous section, the form of the fishery game was defined and represented as a matrix (Table 3). The next task is to assign the payoffs for each strategy combination in the matrix. The following section explains how to obtain the payoffs for each fisher corresponding to each strategy combination. Then, I solve for the outcomes of the game and also the realized payoffs from the outcomes.

ASSIGNING THE PAYOFFS

Strategy Combination (cooperative, cooperative)

Consider the strategy combination (cooperative, cooperative). Given the assumption of a binding agreement and that the two fishers are homogeneous in fishing power and fishing costs. It is obvious that the payoff for this strategy combination is the benefit from the quota harvest assigned for each fisher, half of the total quota. The realized payoff for this strategy is:

$$\pi_{icc} = \delta_i \left[\left(\frac{Q}{2} * P \right) - c * f_i \right]; \tag{12}$$

where Q is the total quota, P is market price per unit of fish weight, c is the cost per unit of fishing effort, and f_i is fishing effort for fisher i.

To find the effort for each fisher, set the total catch equal to the quota,

$$\frac{r * B}{2} = B * \left(1 - \exp\left(- q * f_T\right)\right), \tag{13}$$

where B is the stock size at the beginning of the fishing period and f_T is the total effort for both fishers.

From (13) the total effort is

$$f_T = \frac{-\ln\left(1-\frac{r}{2}\right)}{q}$$

Because each fisher has an equal share in the quota, each will exert half that amount of effort during the fishing season effort

$$f_A = f_B = \frac{-\ln\left(1-\frac{r}{2}\right)}{2q} \tag{14}$$

Finally, the realized profit for fisher i when he and his opponent are both cooperative (π_{icc}) is

$$\pi_{icc} = \delta_i\left[\frac{r*B*P}{4} - c\left(\frac{-\ln\left(1-\frac{r}{2}\right)}{2q}\right)\right] \tag{15}$$

Strategy Combinations (non-cooperative, cooperative) and (cooperative, non-cooperative)

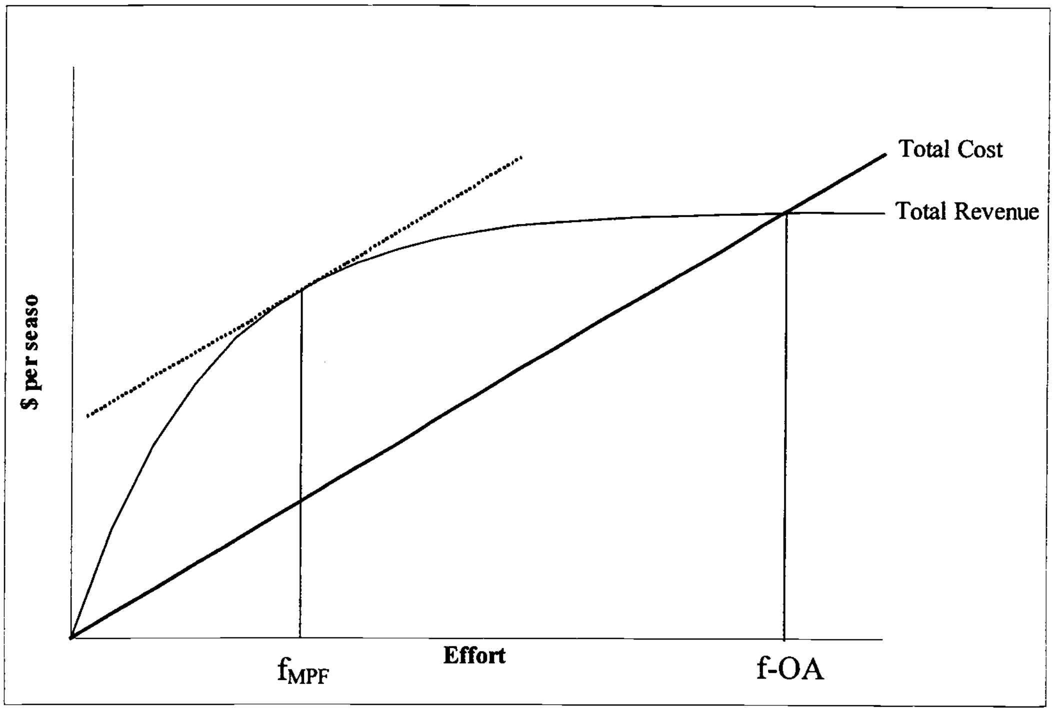
The payoffs (π_{cn}, π_{nc}) and (π_{nc}, π_{cn}), corresponding to the strategy combinations of (cooperative, non-cooperative) and (non-cooperative, cooperative) respectively, represent the case of one fisher cheating and catching more than the quota share, while the other is cooperating and catching only the quota share. To assign payoffs for these strategy combinations assume that one fisher harvests his quota share while the other fisher harvests so as to maximize his profits.

In the short run the total costs of fishing are assumed to be a linear function of effort (Figure 2). Doubling the fishing effort (i.e. spending twice as much time fishing or doubling the units of fishing gear) will also double the costs of fishing. Meanwhile, total revenue as a function of fishing effort first dramatically increases but then gradually levels off and approaches a horizontal asymptote as the fish stock is depleted. The effort level f-OA (Effort at Open Access) is the effort level at which the total fishing costs equals the total revenue. The fishers make only normal profits at the effort level f-OA. The effort level f_{MPF} is the effort level that will produce the maximum profit for the fishery (MPF).

Using the short run catch and effort relationship, the effort that maximizes the profit (f_{MPF}) for the fishery can be calculated by equating marginal revenue with marginal cost,

$$MR = MC$$

Figure 2. Short-run cost and revenue in a fishery



In standard economic analysis, marginal revenue is defined as the change in revenue associated with a change in output. In the analysis here, marginal revenue is the change in revenue associated a change in total fishing effort, which is an input. This alternative approach is often used in fisheries economics (Cunningham, Dunn, and Whitmarsh, 1985). The marginal revenue is

$$MR = \frac{\partial TR}{\partial f} = q * P * B * \exp(-q * f)$$

Similarly, the marginal cost function is

$$MC = \frac{\partial TC}{\partial f} = c$$

When the profit is maximized we have:

$$q * P * B * \exp(-q * f) = c \tag{16}$$

Therefore,

$$f_{MPF} = \frac{-\ln\left(\frac{c}{q * P * B}\right)}{q} \tag{17}$$

Assume that fisher B is the cooperative player and is trying only to catch his quota share. His catch is

$$C_B = \frac{1}{4} r * B \tag{18}$$

and the fishing effort f_B needed to take this catch must satisfy the catch equation

$$B\left(\frac{f_B}{f_{MPF}}\right)(1 - \exp(-q * f_{MPF})) = \frac{1}{4} r * B$$

Hence,

$$f_B = \frac{r^* f_{MPF}}{4(1-\exp(-q^* f_{MPF}))} \tag{19}$$

The realized cooperative profit for B when his opponent chooses the non-cooperative strategy is

$$\pi_{Bcn} = \delta_B \left[\frac{1}{4} r^* B^* P - \left(\frac{r^* f_{MPF} {}^* c}{4(1-\exp(-q^* f_{MPF}))} \right) \right]$$

In general terms, the profit for the fisher who is cooperative while his opponent is non-cooperative can be written

$$\pi_{icn} = \delta_i \left[\frac{1}{4} r^* B^* P - \left(\frac{r^* f_{MPF} {}^* c}{4(1-\exp(q^* f_{MPF}))} \right) \right] \tag{20}$$

Fisher A, who decides not to cooperate, knows the payoff function for cooperation and knows the effort level f_{MPF} that will yield the maximized profit. Therefore, the most benefit that he could get from the fishery is the maximized profit less the profit of fisher B who catches his quota share. As a result, the effort that fisher A should employ is the effort level f_{MPF} minus the effort that fisher B employs

$$f_A = f_{MPF} - f_B,$$

$$= f_{MPF} - \frac{r * f_{MPF}}{4(1-\exp(-q * f_{MPF}))} \tag{21}$$

From the basic catch equation, the catch for fisher A is

$$C_A = B\left(\frac{f_A}{f_{MPF}}\right)(1-\exp(-q * f_{MPF}))$$

$$C_A = B\left(\frac{f_A}{f_{MPF}}\right)(1-\exp(-q * f_{MPF}))'$$

$$\therefore C_A = B\left((1-\exp(-q * f_{MPF})) - \frac{r}{4}\right) \tag{22}$$

Because fisher A has chosen the non-cooperative strategy, his realized payoff is

$$\pi_{Bnc} = (1-\delta_A)\left[B\left[(1-\exp(-q * f_{MPF})) - \frac{r}{4}\right]P - \left(f_{MPF} - \frac{r * f_{MPF}}{4(1-\exp(-q * f_{MPF}))}\right)c\right] \tag{23}$$

We can write, in general, that the non-cooperative profit for fisher i when his opponent is cooperative is:

$$\pi_{inc} = (1-\delta_i)\left[B\left[(1-\exp(-q*f_{MPF}))-\frac{r}{4}\right]P-\left(f_{MPF}-\frac{r*f_{MPF}}{4(1-\exp(-q*f_{MPF}))}\right)c\right] \quad (24)$$

Strategy Combinations (non-cooperative, non-cooperative)

In contrast to the strategy (cooperative, cooperative), the strategy combination (non-cooperative, non-cooperative) implies that there is no binding agreement to restrain harvests and both fishers operate as if they are in an open access fishery. There are no effective regulations that control fishing and the fishers harvest as much as they want. Consequently, the realized payoffs for both fishers are the benefits gained from fishing at the open access level, in which case, fishing revenue equals the total cost of fishing. Therefore, both fishers will get only normal profits of zero.

SOLVING FOR THE PROBABILITY OF COOPERATION

To determine the mixed strategy solutions to the fishery game the strategy choices by each player are assigned probabilities (Table 4). To solve for the probabilities p_A, p_B let us first consider fisher A and solve for his/her probability of choosing each strategy. Given values for the probabilities p_B and 1-p_B to choose the strategies cooperative and non-cooperative respectively, fisher A's payoff when he plays cooperatively is

$$\pi_{Ac}(p_A = 1, p_B) = p_B * \pi_{Acc} + (1-p_B) * \pi_{Acn} \quad (25)$$

Table 4. Fishing game matrix with the assigned payoffs

Fisher B

Fisher A		Cooperative	Non-Cooperative	
	Cooperative	(π_{Acc}, π_{Bcc})	(π_{Acn}, π_{Bnc})	p_A
	Non-cooperative	(π_{Anc}, π_{Bcn})	$(0, 0)$	$1\text{-}p_A$
		p_B	$1\text{-}p_B$	

The payoff when fisher A plays non-cooperatively is

$$\pi_{An}(p_A = 0, p_B) = p_B * \pi_{Anc} + (1 - p_B) * \pi_{Ann}$$

$$= p_B * \pi_{Anc} \tag{26}$$

At the mixed strategy equilibrium fisher A is indifferent between the expected payoffs from the two strategies. Thus, by setting equation (25) equal to equation (26) I can calculate the value for p_B,

$$p_B * \pi_{Acc} + (1 - p_B) * \pi_{Acn} = p_B * \pi_{Acn}$$

$$p_B = \pi_{Acn} \Big/ \left(\pi_{Anc} + \pi_{Acn} - \pi_{Acc}\right) \tag{27}$$

Similarly, the realized payoff for fisher B when he plays cooperatively is

$$\pi_B(p_A, p_B = 1) = p_A * \pi_{Bcc} + (1 - p_A) * \pi_{Bcn} \tag{28}$$

and the realized payoff when he plays non-cooperatively is

$$\pi_B(p_A, p_B = 0) = p_A * \pi_{Bcn} + (1 - p_A) * \pi_{Bnn}$$
$$= p_A * \pi_{Bcn} \tag{29}$$

When fisher B is indifferent between the payoffs from the two strategies, equation (28) is equal to equation (29),

$$p_A * \pi_{Bcc} + (1 - p_A) * \pi_{Bcn} = p_A * \pi_{Bnc}$$
$$p_A = \pi_{Bcn} \Big/ (\pi_{Bnc} + \pi_{Bcn} - \pi_{Bcc}) \tag{30}$$

Having determined values for p_A and p_B, I can then calculate the realized profits from each strategy combination. As can be seen from equations (27) and (30) derived from the previous section, the probabilities of cooperation p_A for fisher A and p_B for fisher B, are functions of the profits. The profits are derived from many parameters: r, B, the fishers' tendencies to cooperate (δ_i), fishing effort (f), fish price (P), and fishing costs (c). Because there are so many parameters in the model, it is difficult to investigate how any given parameter actually influences the model output. In addition, the ranges of values for some parameters have not been fully specified. Here, I manipulate the fishery model so as to specify ranges for all the parameters and to reduce the numbers of parameters in the model.

SPECIFYING RANGES OF VALUES FOR THE PARAMETERS.

The value of r is limited to the range $0 < r < 2$. Because $Q = r/2^* B$, when $r \geq 2$ the quota exceeds the stock size. It is impossible for a fishery to exceed the available stock, therefore r can not exceed 2.

The value of b_i (b_A or b_B) is limited to the range $0 < b_i < 1$. The discount rate (b_i*r) must be less than or equal to r, therefore, the maximum value for the risk coefficient b_i is 1. At b_i's lowest value of zero, the fishers' discounted cooperative benefit is the same as the undiscounted cooperative benefit.

In an unexploited fish stock one would expect the stock size to be approximately equal to the carrying capacity and when there is fishing the stock size should be less than the carrying capacity. We can eliminate one parameter by scaling the initial stock size B by the carrying capacity K,

$$B' = \frac{B}{K}$$

The new variable B' is a dimensionless quantity that should be in the range (0, 1).

After scaling by K, the fisheries model becomes

$$p_i = \frac{\frac{\pi_{j\,cc}}{K}}{\frac{\pi_{j\,nc}}{K} + \frac{\pi_{j\,cc}}{K} - \frac{\pi_{j\,cn}}{K}}$$

$$\frac{\pi_{i\,cc}}{K} = \delta_i * \left[\frac{r * P * B'}{4} + \frac{c'}{q} \frac{\ln\left(1 - \frac{r}{2}\right)}{2} \right], \tag{31}$$

where $c' = \frac{c}{K}$,

$$\frac{\pi_{i\,cn}}{K} = \delta_i * \frac{r}{4} * \left\{ B' * P + \frac{c'}{q} \frac{\ln\left(\frac{c'}{q * P * B'}\right)}{\left(1 - \frac{c'}{q * P * B'}\right)} \right\}, \text{ and} \tag{32}$$

$$\frac{\pi_{i\,nc}}{K} = (1 - \delta_i) * \left\{ \frac{4\left(1 - \frac{c'}{q * P * B'}\right) - r}{4} \left[P * B' + \frac{c'}{q} \frac{\ln\left(\frac{c'}{q * P * B'}\right)}{\left(1 - \frac{c'}{q * P * B'}\right)} \right] \right\} \tag{33}$$

Specifying a New Parameter, rho (ρ)

To further reduce the number of parameters and simplify the model I introduce a new parameter, rho (ρ),

$$\rho = \frac{q * P}{c'} = \frac{q * P * K}{c}$$

This allows me to eliminate two additional parameters. Furthermore, the new variable has an economic interpretation. The term $q*P*K$ is the profit per unit of fishing effort when the stock is unfished and c is cost per unit of fishing effort. Therefore, rho is the ratio of profits to costs when the stock is first subjected to fishing.

Scaling the payoffs in equations (31), (32), and (33) by P, we can rewrite those payoffs as functions of rho:

$$\frac{\pi_{icc}}{KP} = \delta_i * \left[\frac{r * B'}{4} + \frac{1}{\rho} \frac{\ln\left(1 - \frac{r}{2}\right)}{2} \right], \tag{34}$$

$$\frac{\pi_{icn}}{KP} = \delta_i * \frac{r}{4} * \left\{ B' + \frac{1}{\rho} \frac{\ln\left(\frac{1}{\rho * B'}\right)}{\left(1 - \frac{1}{\rho * B'}\right)} \right\}, \text{ and} \tag{35}$$

$$\frac{\pi_{inc}}{KP} = (1 - \delta_i) * \left\{ \frac{4\left(1 - \frac{1}{\rho * B'}\right) - r}{4} \left[B' + \frac{1}{\rho} \left(\frac{\ln\left(\frac{1}{\rho * B'}\right)}{\left(1 - \frac{1}{\rho * B'}\right)} \right) \right] \right\} \tag{36}$$

Specifying a Range of Values for rho.

Because rho is the ratio of profits to costs when a fishery begins, realistic values for rho must be greater than one or the stock would never be exploited, but there is no theoretical upper bound. However, this thesis limits the value of rho to the range 2 to 20. It is a range of profit/cost ratios that is not unrealistic. The lower limit of this range is sensible because it is just slightly larger than the theoretical lower bound. The upper limit would mimic a highly profitable fishery. According to Pinkerton (1989), a profit/costs ratio of 9:1 results in reasonable fisher satisfaction. Therefore, the profit/cost ratio of 20 is high enough to see the influence of rho on the outcomes of the game.

MODEL ANALYSIS

The focus of this thesis is to explore how fish stock size (B') and natural productivity (r) influence the fishers' decision to cooperate. I conducted analyses of the model to investigate the influence of these factors. There are two primary analyses, the investigation of the influences of r and B' on the strategy outcomes of the game and the investigation of how r and B' influence on the fishers' probability to cooperate. The first analysis, which covered a broader range of values for the model's parameters, includes the complete set of strategy outcomes for the model outputs. The second analysis is limited to the set of model outputs that produced mixed strategies, which are obtained from only some combinations of values for r and B' and the other parameters.

STRATEGY OUTCOMES

Different combinations of the values of the parameters in the fishery game, r, B', δ_A, δ_B, and ρ, yield various outcomes of the game, which in general could be pure strategy outcomes of (cooperative, cooperative), (cooperative, mixed), (mixed, cooperative), (non-cooperative, non-cooperative), as well as mixed strategy outcomes. Furthermore, many combinations result in what I describe as negative (cooperative, cooperative) outcomes, which is a special case that differs from the (cooperative, cooperative) outcome mentioned above. Moreover, some combinations yield outcomes that imply situations where there is no fishing.

The factor that determines these outcomes and the no fishing situation is the profits at the payoffs. In general, for pure strategy outcomes, the fishers have either the cooperative or the non-cooperative as their dominant strategy, which means that this responses always result the best payoff for the fishers regardless of which strategy their opponent plays. If both fishers have cooperative strategy as their dominant strategy, the outcome of the game is the pure strategy outcome of (cooperative, cooperative). However, the non-cooperative strategy in the fishery game will never be the dominant strategy for the fishers because the payoff for (non-cooperative, non-cooperative) is zero, whereas the payoffs for the other strategies are positive. The outcomes normally would be either (cooperative, mixed) or (mixed, cooperative) where one fisher has the cooperative strategy as his dominant strategy while the other has no dominant strategy. For example the (cooperative, mixed) outcome occurs when the cooperative strategy is the response for fisher A that yields the largest payoff no matter which strategy fisher B plays, while neither the cooperative strategy nor the non-cooperative strategy is the best response for fisher B. In this situation fisher B is better off by playing a mixed strategy. If both fishers have no dominant strategy the outcome of the game is a mixed strategy outcome. In other words, it is a situation where the game has no pure strategy equilibrium. Table 5 shows examples of pure strategy outcomes and a mixed strategy outcome.

Table 5. Examples of payoff matrices for pure strategy outcomes and a mixed strategy outcome.

A) A (cooperative, cooperative) outcome

Fisher B

		Cooperative	Non-Cooperative
Fisher A	Cooperative	(0.027, 0.027)	(0.024, 0.008)
	Non-cooperative	(0.008, 0.024)	(0,0)

B) A (cooperative, mixed) outcome

Fisher B

		Cooperative	Non-Cooperative
Fisher A	Cooperative	(0.028, 0.024)	(0.024, 0.053)
	Non-cooperative	(0.008, 0.021)	(0, 0)

Table 5. (continued)

C) A (mixed, cooperative) outcome

Fisher B

		Cooperative	Non-Cooperative
Fisher A	Cooperative	(0.028, 0.027)	(0.024, 0.012)
	Non-cooperative	(0.428, 0.024)	(0, 0)

D) A mixed strategy outcome

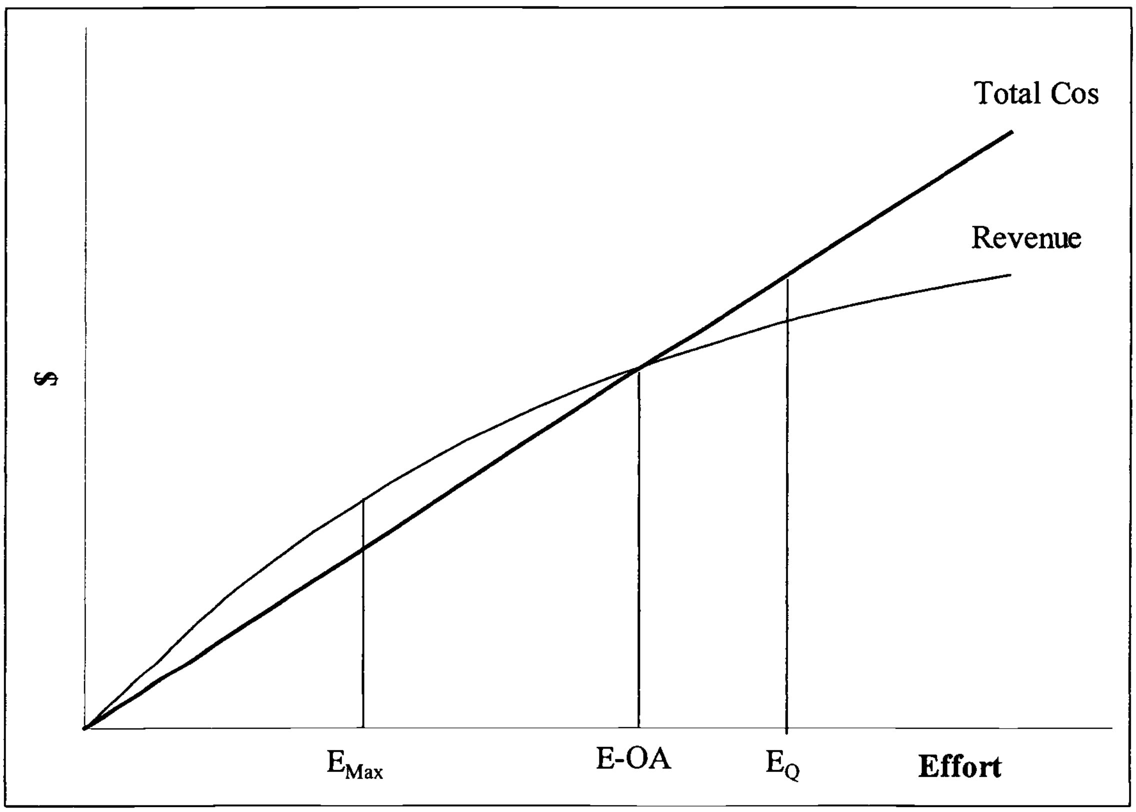
Fisher B

		Cooperative	Non-Cooperative
Fisher A	Cooperative	(0.021, 0.022)	(0.016, 0.037)
	Non-cooperative	(0.046, 0.017)	(0,0)

Figure 3 shows a special case that forces a negative (cooperative, cooperative) outcome. This case occurs when the catch quota is larger than the catch that generates zero profit. If the fishers catch their quota shares they will lose money because they need to employ the level of effort at the quota (E_Q) at which the fishing cost is greater than fishing revenue. Both fishers are better off if they catch less than their quota shares and are, therefore, forced into being cooperative and catching less than their quota shares.

When the catch quota is smaller than the catch that generates zero profits, the fishers can voluntarily accept their quota shares—the catch quota requires level of effort less than the effort level at the open access fishery (E-OA).

Figure 3. The special case where the catch quota is larger than the catch that generates zero profit.



The no fishing situation arises when the fishing revenues are less than the fishing costs. This can occur when the stock is depleted, or when the fish price is too low relative to the cost of fishing. Mathematically, the no fishing situation occurs whenever

B' < 1/rho. The fishers will go fishing only when they can make profits, which is when their revenue is greater than their fishing costs:

$$P * B * q > c$$

$$\therefore B' > \frac{1}{\rho}$$

THE INFLUENCE OF r AND B' ON THE STRATEGY OUTCOMES OF THE GAME

Despite an attempt to reduce the numbers of parameters, there still are five parameters in the model. It is difficult to pinpoint which parameters are most important and how they influence on the outcomes. One way to investigate the influence of each parameter in a model is to vary them one at a time while fixing the others. Because this thesis is concerned with the influence of biological parameters on fishers' cooperation, I mainly investigate the influences of r and B' on the outcomes of the game given a limited set of fixed values for b_A, b_B, and rho. Subsequently, the question arises—what values of these parameters should I use?

A criterion for fixing the values of b_A and b_B can be based on hypothetical situations that probably exist in a real fisheries system. For example, in practice we may have a fisheries system in which all the fishers are homogeneous—where the fishers have the same tendencies to cooperate and attitudes towards uncertainty in the fish stock. In this situation, the values of b_A and b_B are the same. Alternatively, we may have a fisheries system where the fishers are heterogeneous—where the fishers' tendencies to cooperate differ from one another. Therefore, the investigation of the influence of r and B' on the outcomes of the game will be considered under various sets of values for b_A and b_B. Two main situations are when the fishers are homogeneous and when they are heterogeneous. Each of these two general situations will be further classified into more specific cases, according to the values of b_A and b_B:

Homogeneous Fishers.

The case of homogeneous fishers can be subdivided into two situations where both fishers have either high or low tendencies to cooperate. The outcomes from the two situations may differ from one another. This situation is then further classified into two cases:

Both fishers have high tendencies to cooperate. In this case, the fishers have the same low value for the risk coefficient, $b_A = b_B = 0.3$.

Both fishers have low tendencies to cooperate. This case is similar to the first one in that the fishers have the same value for the risk coefficient, but the coefficient is high, $b_A = b_B = 0.8$.

Heterogeneous Fishers.

The situation of heterogeneous fishers can be classified into three specific cases:

Both fishers have high tendencies to cooperate. In this case, the values of the fishers' risk coefficients to cooperate are low, but they are differ from each other, $b_A = 0.2$, $b_B = 0.4$.

Both fishers have low tendencies to cooperate. Likewise, the values of the fishers' risk coefficient differ from each other, but in this case are high, $b_A = 0.7$, $b_B = 0.9$.

One fisher has a high tendency to cooperate, while the other has a low tendency to cooperate. For this last case, the two fishers are totally opposite in their tendencies to cooperate, with an extremely low value of the risk coefficient for one fisher and an extremely high value for the other, $b_A = 0.3$, $b_B = 0.8$.

The risk coefficients vary on a scale from 0.0 to 1.0, and the tendency to cooperate varies inversely with the coefficient. The higher the value of the risk coefficient, the lower is the tendency to cooperate. For example, if fisher A and fisher B have risk coefficients of 0.4 and 0.6 respectively, then, fisher A has a higher tendency to cooperate than fisher B. Table 6 shows the pairs of values for the risk coefficient of the two fishers that are used in the analysis.

In these analyses (Table 6) I arbitrarily fix the value of rho to be equal to 6, which is neither extremely low nor extremely high.

Given the above conditions, the analysis then centers on exploring how the outcomes of the game change over the ranges of value for r and B', given the various specific values for b_A, b_B, and the fixed value for rho. Subsequently, I vary the value of rho to see how it influences the outcomes of the game.

In sum, there are two main questions for this model analysis to answer:

1. How r and B' influence the outcome of the game when the fishers' risk coefficients, which reflect fishers' tendencies to cooperate, are taken into account?

2. How r and B' influence the outcomes of the game when the profit/cost ratio (rho) is also taken into account?

Table 6. The fishers' risk coefficients used in the analysis.

Situations	Cases	b_A	b_B
Homogeneous Fishers	High value for the risk coefficient	0.8	0.8
	Low value for the risk coefficient	0.3	0.3
Heterogeneous Fishers	High values for the risk coefficients	0.7	0.9
	Low values for the risk coefficients	0.2	0.4
	Wide range in risk coefficient values	0.3	0.8

MIXED STRATEGIES: THE INFLUENCES OF r AND B' ON FISHERS' PROBABILITY TO COOPERATE

The other primary analysis investigates how the fishers' probabilities to cooperate are influenced by the values of r and B'. The strategy space for this analysis is limited to mixed strategies. The analysis of the influences of r and B' on the strategy outcomes indicated that the mixed strategies solutions are most likely to occur when both fishers have low tendencies to cooperate, either when the fishers are homogeneous or heterogeneous. I present results for the case of heterogeneous fishers where both fishers have low tendencies to cooperate ($b_A = 0.7$, $b_B = 0.9$). The results for the heterogeneous situation show the influences of r and B' on the fishers' probabilities to cooperate. They also allow us to compare the probabilities of cooperation between the two fishers, who differ in their tendencies to cooperate.

Similar to the first primary analysis, I fix the value of rho equal to 6.0. Therefore, we are looking at the same strategy outcomes as in the case of heterogeneous fishers with $b_A = 0.7$ and $b_B = 0.9$.

V. MODEL ANALYSIS RESULTS

I present the results in two main sections. The first section is general results from the primary analysis of the influences of the intrinsic growth rate (r) and stock size (B') on the strategy outcomes of the game. The second section is the results from the particular outcomes of the game that are mixed strategies. The first section includes results from the investigation of the influences of r and B' on the strategy outcomes for different sets of values for the fishers' tendencies to cooperate and when taking into account the profit/cost ratio (rho).

Recall that a strategy outcome is an equilibrium solution of the game, which indicates the strategies that the players choose to play. In the fishery game, the strategy outcomes could be either (cooperative, cooperative), (cooperative, mixed), (mixed, cooperative), (non-cooperative, non-cooperative), or mixed strategies. For convenience in discussing the interpretation and implications of the fishery game, I classify the strategy outcomes into two groups, desirable and undesirable outcomes. The desirable outcomes are those that promote cooperation among the fishers in the cooperative organization. The desirable outcomes are the (cooperative, cooperative) strategy outcomes in which both fishers are voluntarily cooperative. The undesirable outcomes are those outcomes that detract from cooperation among the fishers. They include the strategy outcomes (cooperative, mixed) and (mixed, cooperative), mixed strategies, as well as the situation where there is no fishing. I also consider as an undesirable outcome the (cooperative, cooperative) strategy outcome from the special case wherein the catch quota is larger than the catch that generates zero profits. For convenience in distinguishing between the two different (cooperative, cooperative) situations, I specify the (cooperative, cooperative) situation where the fishers are voluntarily cooperative as positive (cooperative, cooperative) and specify the other where the fishers are forced to cooperate as negative (cooperative, cooperative).

THE INFLUENCE OF r AND B' ON THE STRATEGY OUTCOMES OF THE GAME

Generally, both r and B' have an influence on the outcomes of the game as well as on the fishers' probability to cooperate. But their specific influence depends on the particular values for the fishers' tendencies to cooperate (δ_A, δ_B) and the ratio of profits to the fishing costs (ρ). I present general results to demonstrate: (1) the influences of r and B' on the outcomes of the game when the fishers' risk coefficients (b_A, b_B) are taken into account, and (2) the influences of r and B' on the outcomes of the game when all parameters, including rho, are taken into account.

INFLUENCES OF r AND B' ON STRATEGY OUTCOMES OF THE GAME WHEN b_A AND b_B ARE TAKEN INTO ACCOUNT

The effect of r or B' on the outcomes of the game cannot be meaningfully interpreted without also considering the fishers' tendencies to cooperate (δ_A, δ_B). Parameters r and B' appear to influence the outcomes of the game differently depending upon the homogeneity/heterogeneity in the fishers' tendencies to cooperate, which are determined by the fishers' risk coefficients b_A and b_B. Even in the situation where the fishers are homogeneous (or heterogeneous), the outcomes of the game will differ between two cases that have different values for b_A and b_B, unless the two cases have very close values for b_A and b_B.

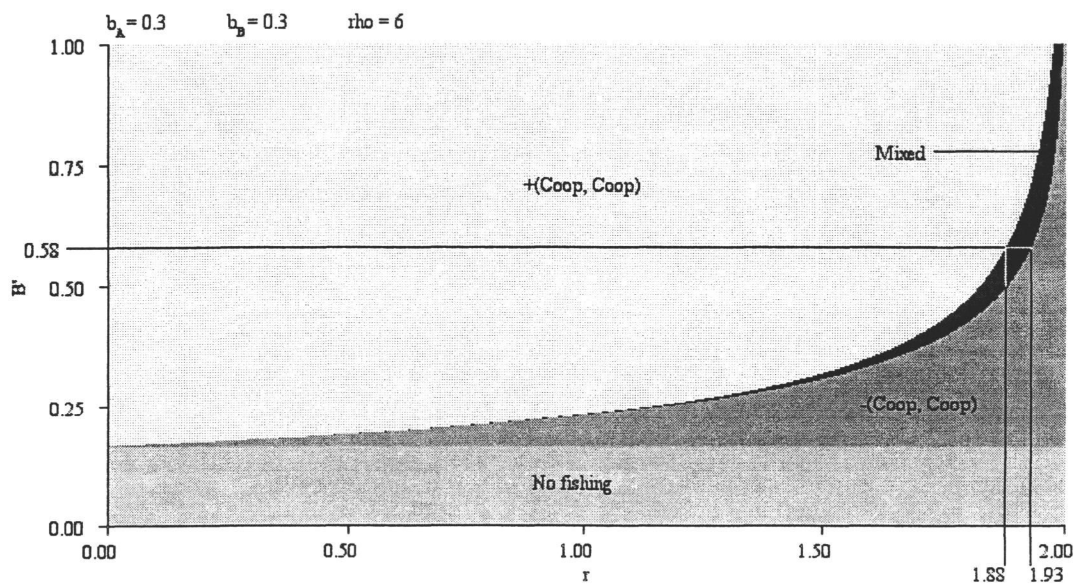
Homogeneous Fishers.

When the fishers are homogeneous in their risk coefficients and thus have the same tendency to cooperate, both fishers will have the same strategy solution. If fisher A selects the cooperative strategy fisher B will do the same. However, the outcomes when the fishers have high tendencies to cooperate differ from those for which the fishers have low tendencies to cooperate. When the fishers have high tendencies to cooperate, the most frequent outcomes of the game are the strategy outcomes of positive (cooperative, cooperative). That is to say, the fishers are voluntarily cooperative for most combinations of parameters r and B'. As the fishers' tendencies to cooperate decrease, the outcomes are more likely to shift from desirable outcomes to undesirable outcomes. The following two cases contrast the outcomes where the fishers have high versus low tendencies to cooperate.

Both fishers have high tendencies to cooperate (low values for the risk coefficients). Figure 4 shows a map of strategy outcomes of the fishery game when both fishers have risk coefficient values of 0.3, given a fixed value for the profit/cost ratio (rho) of 6. The map shows the combinations of r and B' that result in each of the different strategy outcomes. When both fishers have high tendencies to cooperate, the strategy outcomes of the game usually are the positive (cooperative, cooperative) outcomes where both fishers voluntarily harvest only their quota shares. These outcomes cover the area corresponding to values of B' > 1/rho and values of 0.00 < r < 0.44.

However, as the value of r increases the boundary for the area of positive (cooperative, cooperative) outcomes occurs at higher values of B'. A region of negative (cooperative, cooperative) outcomes occurs at high values of r and low values of B'. Between the area of positive (cooperative, cooperative) outcomes and the area of negative (cooperative, cooperative) outcomes is the area where both fishers play mixed strategies. The no fishing situation covers the area of low value of B' < 1/rho, across all the values of r.

Figure 4. Strategy outcomes of the game at various combinations of r and B', when $b_A = b_B = 0.3$, and rho = 6.



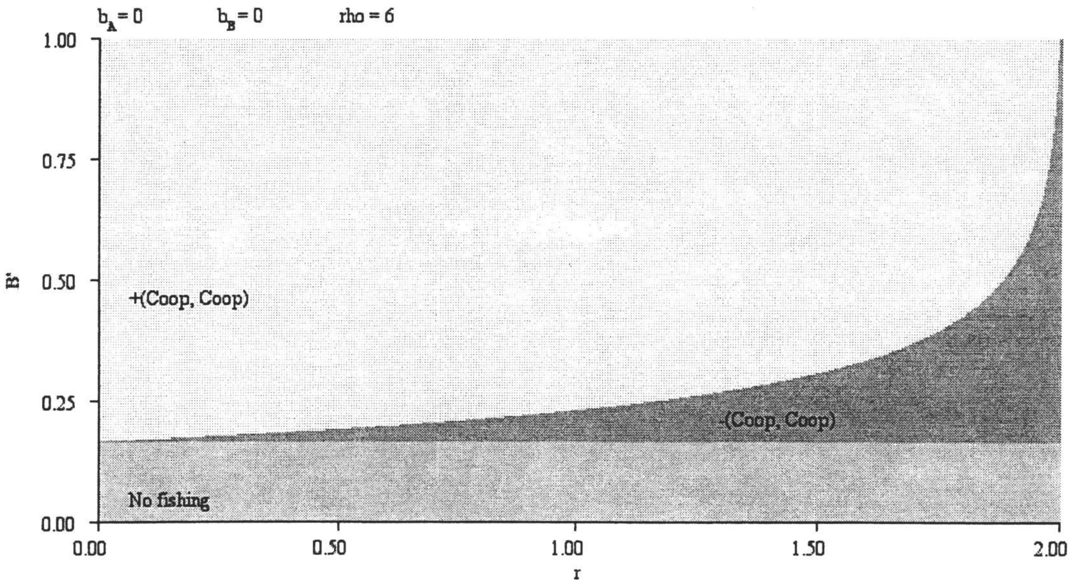
In general, as the value of r increases the strategy outcome shifts from a desirable outcome, positive (cooperative, cooperative), to an undesirable outcome. This can be seen at a fixed value of B', such as at B' = 0.58. The strategy outcome is positive (cooperative, cooperative) where $0.00 < r < 1.88$. Where $1.88 < r < 1.93$ the strategy outcome is mixed and then becomes negative (cooperative, cooperative) where $r > 1.93$. Because the relative stock size (B') and rho are the same across the values of r, it seems that the latter switch is affected by the increase in r, which causes a decrease in the fishers' tendencies to cooperate. Given fixed values for b_A and b_B, the fishers' tendencies to cooperate (δ_i) decrease as the value of r increases because the tendency to cooperate is an inverse function of r and the fishers' risk coefficient,

$$\delta_i = \frac{1}{1+(b_i * r)}$$

However, if b_I is zero then the term $b_I * r$ is also zero and the tendency to cooperate is independent of r. The map from the case of $b_i = 0$ (Figure 5) shows that the outcomes of the game have a similar pattern as the outcomes from $b_i = 0.3$ and r still affects the outcomes. This effect of r on the boundary between positive and negative outcomes is not due to the fishers' tendencies to cooperate but comes directly from the way that r is imbedded in the payoff function.

The outcomes that result in the no fishing situation exist where $B' < 1/\text{rho}$, across all values of r and of b_A and b_B. For the values of b_A, b_B, and rho given above, this situation covers the area where B' ranges from 0.00 to 0.16. The low values of B' imply that the stock has been depleted; the current stock size is very low relative to the unfished stock. The profit from fishing is so low that it is outweighed by the fishing cost.

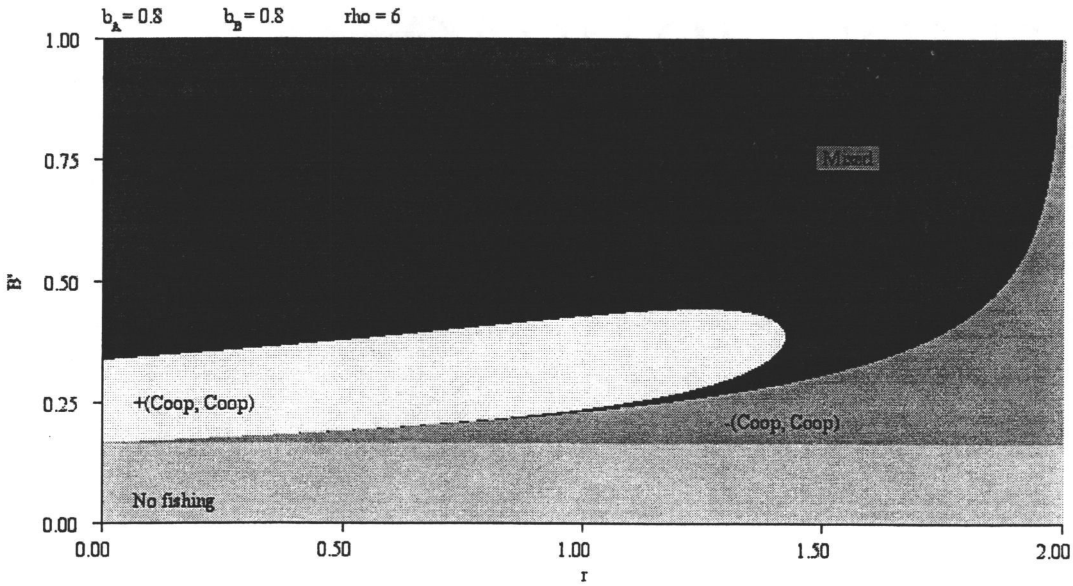
Figure 5. Strategy outcomes of the game at various combinations of r and B', when $b_A = b_B = 0.0$, and rho = 6.



Both fishers have low tendencies to cooperate (high values for the risk coefficients). In contrast to the outcomes when both fishers have high tendencies to cooperate, the outcomes when both fishers have low tendencies to cooperate ($b_A = b_B = 0.8$) are dominated by undesirable outcomes, especially mixed strategies (Figure 6). The only area of positive (cooperative, cooperative) outcomes is the small area where the values of B' are relatively low (from 0.19 to 0.34) and the values of r are in the low to medium range (from 0.00 to 1.40).

The no fishing situation occurs at low value of B', where B' < 1/rho, across all values of r, b_A, and b_B. The situation where both fishers are forced to cooperate has a similar pattern as in the case where $b_A = b_B = 0.3$. It starts at the value of B' = 0.19 and moves upward to high values of B' as the value of r increases.

Figure 6. Strategy outcomes of the game at various combinations of r and B', when $b_A = b_B = 0.8$, and rho = 6.



When both fishers have low tendencies to cooperate, the mixed strategies tend to occur at high values of B' and also at high values of r. When the fishers have low tendencies to cooperate, the high value of B' yields higher maximized profit, which provides an incentive for the fishers to play mixed strategies. The high value of r induces the fishers to play mixed strategies when facing opponents who have low tendencies to cooperate. The more productive and variable the stock, the lower the fishers tendencies to cooperate. However, because there is no dominant strategy for both fishers, the outcomes of the game end up with mixed strategies (Table 7). If the game has cooperation as the dominant strategy for both fishers, the cooperative payoff for each fisher will be the highest regardless of which strategy their opponents would play (as in the case where both fishers have high tendencies to cooperate). Alternatively, if the game has non-cooperation as the dominant strategy for both fishers, the non-cooperative payoffs for each fisher will be the highest regardless which strategy their opponents would play. The matrix game in the Table 7 shows neither of these two situations. Therefore, the best response for both fishers is to play mixed strategies.

Table 7. Matrix game where both fishers play mixed strategies, given $r = 0.72$, $B' = 0.49$, rho = 6, and $b_A = b_B = 0.8$. The payoffs are presented in terms of the profits relative to the unfished stock.

Player B

		Cooperative	Non-cooperative
Player A	Cooperative	(0.032, 0.032)	(0.025, 0.038)
	Non-cooperative	(0.038, 0.025)	(0, 0)

Logically, one might expect that the area of the mixed strategy outcomes should have spread out as the values of B' and r increase. Instead, the area of the mixed strategy outcomes is reduced and is replaced by the positive (cooperative, cooperative) outcomes, approximately at the range of B' from 0.19 – 0.43 and the range of r from 0.44 – 1.40. In particular to the fishers who have low tendencies to cooperate, the maximized profit from the fishery at these ranges of B' and r is not high enough to leave an excessive profit after taking into account the profit at the quota. The fishers, therefore, are better off playing the cooperative strategy because their payoffs from playing this strategy are the highest regardless of which strategies their opponent would play.

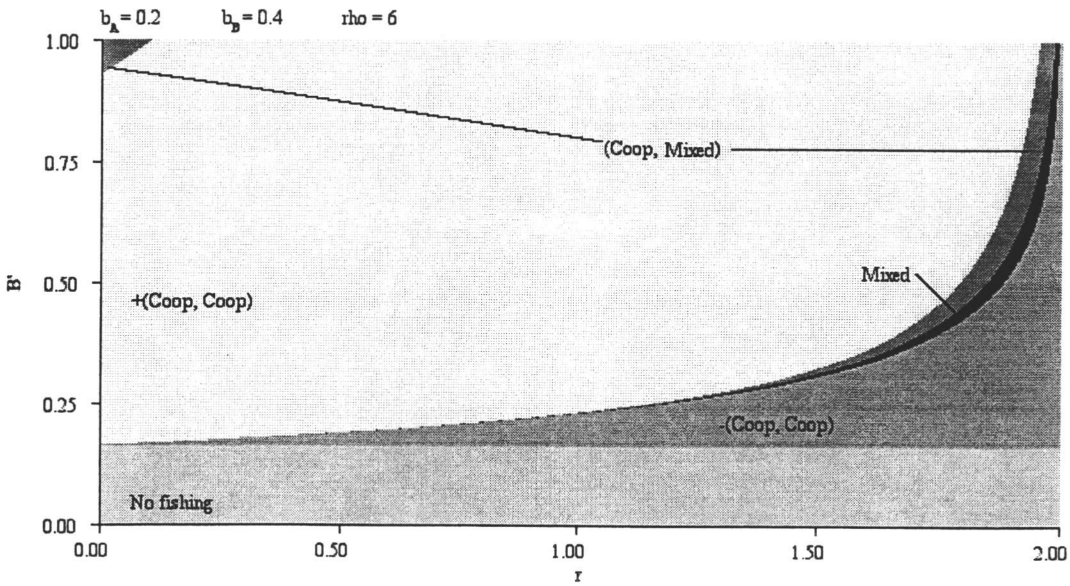
Compare the strategy outcomes from Figures 4 and 6. The most and least frequent strategy outcomes on the two maps are swapped. Also, notice that the only difference between the parameters for these two cases are the values of the fishers' risk coefficients, b_A and b_B. The opposite outcomes from the two cases evidently indicate the strong influence of the fishers' risk coefficients. The coefficients represent the fishers' preferences in responding to stock uncertainty. The fisher whose coefficient is high is more willing to take a gamble on stock uncertainty than the fisher whose coefficient is low. Consequently, the fisher who has a high risk coefficient is less likely to cooperate. The most frequent outcome from the case where the two fishers have a low value for the risk coefficient is positive (cooperative, cooperative), while the outcome where the two fishers have a high value for the risk coefficient is usually mixed strategies.

Heterogeneous fishers.

The results from the two cases where the fishers are homogeneous show that the fishers' tendencies to cooperate influences the outcomes of the game just as much as r and B'. The results in this part of the model analysis show that not only the fishers' tendencies to cooperate but also the heterogeneity of the fishers has an influence on the outcomes. But the influence of heterogeneity appears to be minor when compared to the influence from the magnitude of the fishers' tendencies to cooperate.

Both fishers have high tendencies to cooperate. Despite the difference between the fishers' tendencies to cooperate, the pattern of outcomes in this case is similar to the case of homogeneous fishers whose tendencies to cooperate are high (Figure 7). The positive (cooperative, cooperative) outcome is the most frequent strategy outcome as in the homogeneous cases, the no fishing situation occurs within the same range of B' and across the entire range of r. Also, the negative (cooperative, cooperative) outcomes in this case spread out and move upward as the value of r increases as seen in the previous cases.

Figure 7. Strategy outcomes of the game at various combinations of r and B', when $b_A = 0.2$, $b_B = 0.4$, and rho = 6.



The only difference is that there are (cooperative, mixed) strategy outcomes when the fishers are heterogeneous. In this setting fisher A has a higher tendency to cooperate than fisher B because he has a lower value of the risk coefficient. The results show that fisher A plays a cooperative strategy, while fisher B plays mixed strategies. Because of his/her higher tendency to cooperate, fisher A appears to value the cooperative payoff more than fisher B does. As a result, the cooperative strategy becomes the dominant strategy for him/her; that is to say fisher A is always better off by playing the cooperative strategy (Table 8). In contrast, fisher B appears to value the cooperative payoff less than fisher A. Consequently, fisher B has no dominant strategy and he/she is better off by playing mixed strategies, playing the cooperative and non-cooperative strategies randomly.

Table 8. Matrix game where fisher A plays the cooperative strategy, while fisher B plays mixed strategies, given r = 1.48, B' = 0.31, rho = 6, b_A = 0.2, and b_B = 0.4. The payoffs are presented in terms of the profits relative to the unfished stock.

		Player B	
		Cooperative	Non-cooperative
Player A	Cooperative	(0.095, 0.090)	(0.078, 0.096)
	Non-cooperative	(0.051, 0.074)	(0, 0)

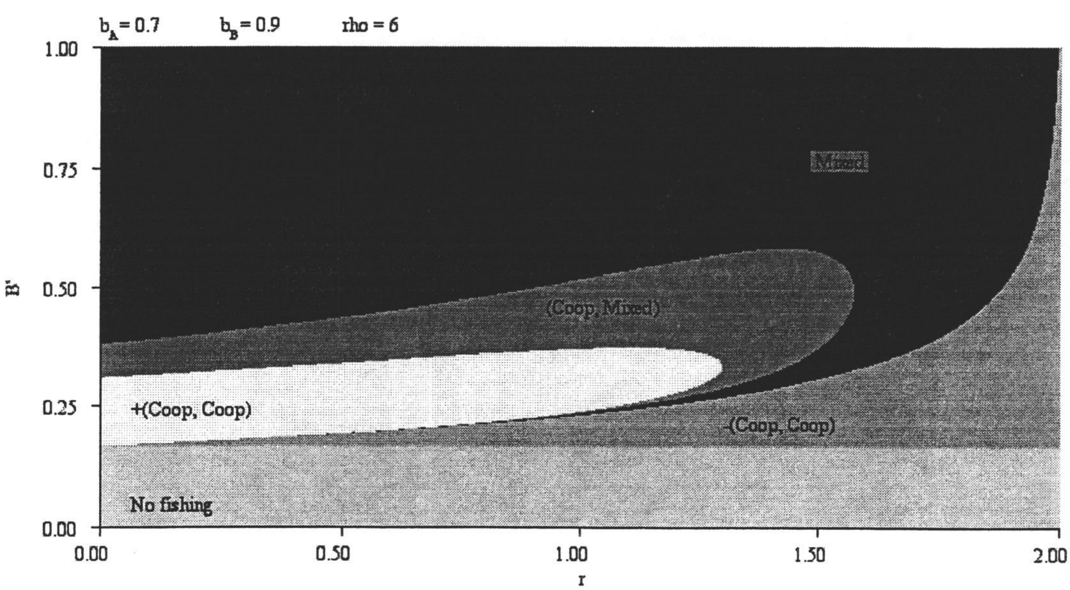
A few mixed strategy outcomes occur between the areas of (cooperative, mixed) outcomes and the negative (cooperative, cooperative) outcomes. Therefore, the direction of the outcomes in the area above the area of no fishing shifts from desirable outcomes of positive (cooperative, cooperative) to undesirable outcomes as the value of r increases. However, the area of undesirable outcomes decreases as the value of B' increases. The direction of the outcomes indicates that even though the fishers have high tendencies to cooperate, high values of r cause undesirable outcomes, particularly with low values of B'. The highly productive and heavily fished stock has more impact on the fishers' decision to cooperate than their tendencies to cooperate. Despite their high tendencies to cooperate, the fishers are less willing to cooperate if the stock is highly productive and heavily fished. In contrast, at higher values of B' the undesirable outcomes occur when the value of r is extremely high. For example, at high values of B' (B' > 0.8) the positive (cooperative, cooperative) outcomes extend until r = 1.96. Therefore, when the fishers have high tendencies to cooperate the fishery is more likely to result in a cooperative environment if the stock has not been depleted severely, despite the high productivity of the stock and the heterogeneity of the fishers.

Both fishers have low tendencies to cooperate. In contrast to the case where the heterogeneous fishers have high tendencies to cooperate, when the heterogeneous fishers have low tendencies to cooperate the most frequent strategy outcomes are mixed strategies (Figure 8). Additionally, the results show that there are many more strategy outcomes of (cooperative, mixed) in this case than in the previous one. The area of the (cooperative, mixed) outcomes occurs between the area of mixed strategies and the positive (cooperative, cooperative) outcomes. Meanwhile, the areas for no fishing and negative (cooperative, cooperative) outcomes have the same pattern as in all the previous cases.

The rationale for why certain outcomes occur at certain ranges of r and B' can be explained in the same fashion as in the previous cases. Because of the low tendencies to cooperate, one fisher is more likely to play mixed strategies. The solution in this case consequently yields many more (cooperative, mixed) outcomes than the case where the fishers have high tendencies to cooperate. The contrast in the most frequent strategy outcomes between the case where the fishers have high and low tendencies to cooperate

(Fig. 7 versus Fig. 8) indicates that the magnitude of the fishers' tendencies to cooperate is more important than the difference between fishers' tendencies to cooperate. The factors that really control the strategy outcomes are b_A and b_B rather than (b_A - b_B). As long as the fishers have similar tendencies to cooperate, i.e. both have high or both have low tendencies, the outcomes are more likely to be positive (cooperative, cooperative) outcomes or mixed strategies respectively. The heterogeneity of the fishers' tendencies to cooperate results in a high tendency to cooperate for one fisher and a low tendency to cooperate for his opponent, which in turn results in a dominant cooperative strategy for the one fisher while his opponent has no dominant strategy; the outcomes are then (cooperative, mixed).

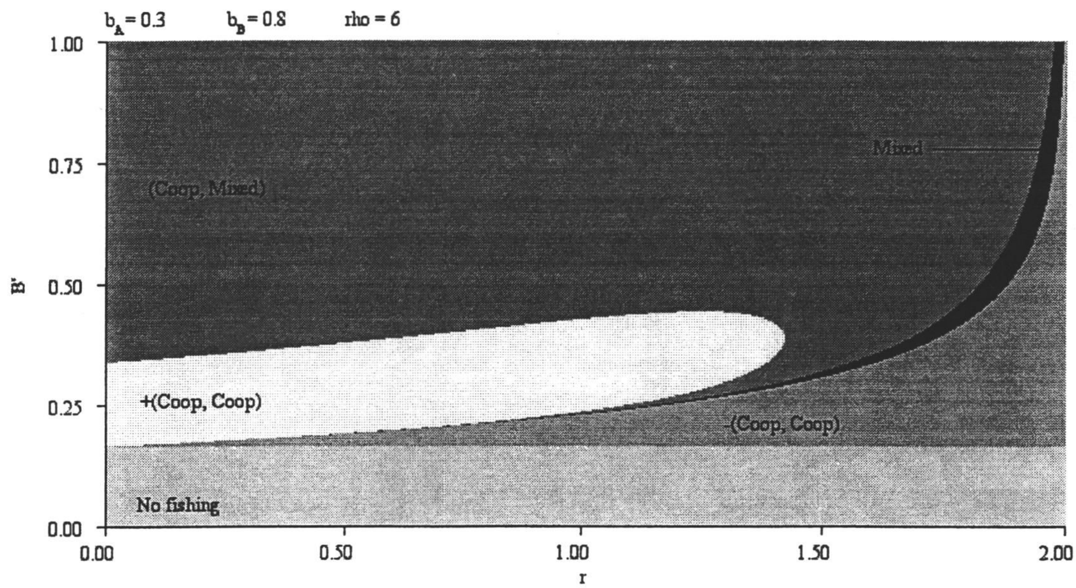
Figure 8. Strategy outcomes of the game at various combinations of r and B', when $b_A = 0.7$, $b_B = 0.9$, and rho = 6.



One fisher has high tendency to cooperate, while the other has low tendency to cooperate. Figure 9 shows the strategy outcomes for the case where the two fishers' tendencies to cooperate are opposite. Unlike the outcomes of the two previous cases where the fishers are heterogeneous, when the fishers are extremely different in their tendencies to cooperate the most frequent strategy outcome is the (cooperate, mixed) outcome. However, the pattern of the positive (cooperative, cooperative) outcomes is similar to that of the outcomes for the cases where the fishers have high tendencies to cooperate, either when fishers are homogeneous (Fig. 4) or heterogeneous (Fig. 7). This area occurs at low values of $0.18 < B' < 0.42$ and at values of $0.00 < r < 1.39$. A limited area of strategies occurs between the areas of (cooperative, mixed) outcomes and negative (cooperative, cooperative) outcomes, as well as between the positive and negative (cooperative, cooperative) outcomes. The areas of no fishing and negative (cooperative, cooperative) outcomes have the same pattern as in all the previous cases.

The reason this case has (cooperative, mixed) outcomes so frequently is obvious. Because the two fishers are opposite in their tendencies to cooperate, one fisher tends to have the cooperative strategy as his dominant strategy while the other has no dominant strategy. This area occurs at high values of B' where the maximized profit is high. The excessive profit from fishing at the quota gives incentive to fisher B, who has a low tendency to cooperate, to catch more than his quota share. He would rather not always catch over his share due to the possibility that the other fisher might retaliate by playing a non-cooperative strategy. To avoid having zero profit, he is better off playing mixed strategies. Meanwhile fisher A, who has high tendency to cooperate, appears to have the cooperative strategy as his dominant strategy because he highly values the cooperative payoff. Having a healthy fishery, in which the stock is not heavily depleted, induces fisher A to be satisfied with the profit from his quota share, which he perceives and values as being highly profitable.

Figure 9. Strategy outcomes of the game at various combinations of r and B', when $b_A = 0.3$, $b_B = 0.8$, and rho = 6.



The area of positive (cooperative, cooperative) outcomes occurs below the area of (cooperative, mixed) outcomes, at lower values of B'. The range of values for B', 0.18 < B' < 0.42 indicates a heavily depleted stock. In this area, both fishers are better off cooperating. The excessive profit is too low and it is not worthwhile for the fishers to catch more than their quota shares. However, within this same range for B' there are also (cooperative, mixed) outcomes that mostly occur at higher values of r, r > 1.11. Recall that at high values of r, the fishers who have low tendencies to cooperate are more likely to play a mixed strategy. Therefore, the area between the positive (cooperative, cooperative) outcomes and the mixed strategy outcomes in this range for B' is an area of (cooperative, mixed) outcomes.

The tiny area of mixed strategies located between the area of (cooperative, mixed) outcomes and negative (cooperative, cooperative) outcomes is more likely to occur at higher values of r. This implies that a highly productive and variable stock provides an incentive to catch over the quota shares for both fishers, especially when the stock is not depleted. The high productivity (and high variability) of the stock decreases the fishers' tendencies to cooperate. When the fishers' tendencies to cooperate are lower, the incentive to play mixed strategies is greater than when the stock is only slightly depleted.

In sum, the fishers' tendencies to cooperate play an important role in the outcome of the game in that the fishers who have high tendencies to cooperate are more likely to play a cooperative strategy. The reason for this is that when the fishers have high tendencies to cooperate, they place a greater value on the cooperative payoff than do those who have lower tendencies to cooperate. In contrast, the fishers who have low tendencies to cooperate are more likely to play mixed strategies because they value the cooperative payoff less than those who have high tendencies to cooperate. As a result, the fishers with high tendencies to cooperate have no dominant strategy. They therefore end up playing mixed strategies.

Heterogeneity also an important influence on the outcome of the game. Theoretically, if the degree of heterogeneity is high, it seems logical that the outcomes would be more likely to be undesirable. The difference between fishers' tendencies to cooperate results in different strategies being played by the two fishers, which is an undesirable outcome; such as (cooperative, mixed) or (mixed, cooperative). However, the degree of heterogeneity appears to have only a minor influence compared to the value of the fishers' tendencies to cooperate. As can be seen from the results in the heterogeneous case where both fishers have low tendencies to cooperate (Fig. 8), the outcomes are mostly undesirable. In contrast, most of the outcomes are desirable in the case of heterogeneous fishers where both have high tendencies to cooperate (Fig. 7). The outcomes from the last case, where the fishers are extremely different in their tendencies to cooperate (Fig. 9), are also mostly undesirable. However, the undesirable (cooperative, mixed) outcomes are more likely to be influenced by fisher B's low tendency to cooperate.

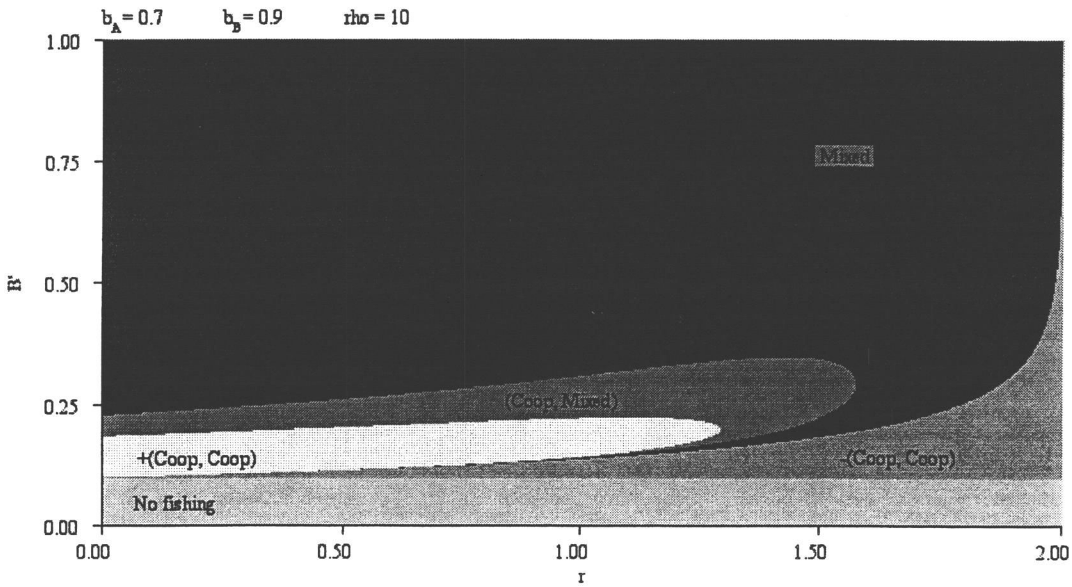
The areas of no fishing and the negative (cooperative, cooperative) outcomes are the same in all cases. This is because the boundaries for these two situations are based on economic constraints that have nothing to do with the fishers' tendencies to cooperate. The no fishing situation is identified by the constraint of profit being less than fishing cost. Meanwhile, the situation of negative (cooperative, cooperative) outcomes is identified by the constraint that the maximum profit is less than the profit at the quota. Both profits are calculated without regard to of the fishers' tendencies to cooperate (Chapter 4, Assigning the Payoffs).

INFLUENCES OF r AND B' ON OUTCOMES OF THE GAME WHEN RHO IS ALSO TAKEN INTO ACCOUNT.

Rather than having direct influence on the outcome of the game, rho actually helps promote the most widespread strategy outcome of the game. For example, the area of mixed strategy outcomes, which is the most frequent strategy outcome for the case of homogeneous fishers with low tendencies to cooperate, will increase as the value of rho increases. To see the effect of rho compare the area of the mixed strategies in Figure 8 and 10. The area of the mixed strategies in Figure 8, where rho = 6, is smaller than the area of the mixed strategies in Figure 10, in which rho = 10. Meanwhile, the areas for the other strategy outcomes shrink as the value of rho increases. These include the area of no fishing and the negative (cooperative, cooperative) outcomes, which did not vary among all previous cases because rho was the same for all the previous cases. At higher values of rho the no fishing area occurs in a narrow range of 0.00 < B' < 0.06, but still across all value of r, b_A, and b_B. Also, the area of negative (cooperative, cooperative) outcomes occurs at lower values of B' and for a narrower range of B'. However, the shape of this area is similar to those seen in the other cases; spreading out and moving upward at higher values of r. The area of positive (cooperative, cooperative) outcomes still has the same shape as in the other cases, but occurs for a narrower range of B'.

These features of enlarging and reducing areas for the different strategy outcomes are caused by the change in profit in the fishery. High values of rho increase the profit from fishing, which provides increased incentive to catch more than quota, particularly for fishers who have low tendencies to cooperate. Compare the case of low and high values of rho (Fig. 8 versus Fig. 10). The area in the range of 0.21 < B' < 0.42 is the area mostly positive (cooperative, cooperative) outcomes when the value of rho is 6, while this area has mostly mixed strategy outcomes when the value of rho is 10. When the value of rho is high the profit from the fishery is still pleasant even at lower values of B'. As a result, the fishers who already have low tendencies to cooperate have incentive to catch more than their shares. Consequently, when the value of rho is high, the area of mixed strategy outcomes expands into the area where the values of B' are lower.

Figure 10. Strategy outcomes of the game at various combinations of r and B', when $b_A = 0.7$, $b_B = 0.9$, and rho = 10.



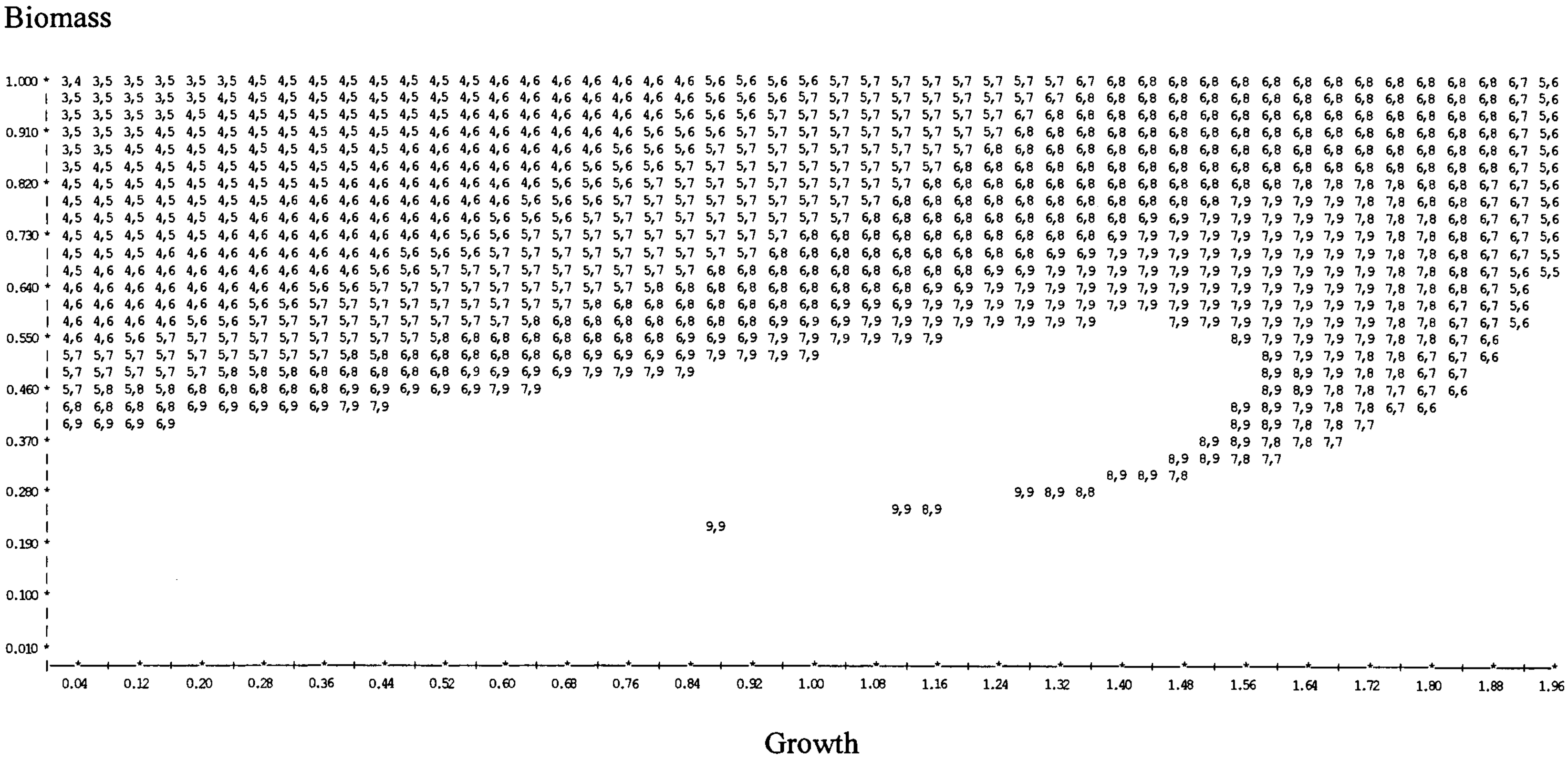
In contrast, greater profit reduces the area for the other strategy outcomes and it also shifts those outcomes to lower values of B'. These lower values of B' represent a heavily depleted stock. Despite a high profit/cost ratio, the maximized profit from the fishery is not high enough for the fishers to catch more than their quota shares. Therefore, in the area with low values for B' (0.12 < B' < 0.24) and low to medium values for r (0.00 < r < 1.40) the most frequent outcomes are positive (cooperative, cooperative) outcomes. The area with lower values for B' at high r most frequently yield negative (cooperative, cooperative) outcomes. The combination of a highly productive and variable stock and the fishers' tendencies to cooperate make the fishers perceive negative profit from the fishery if they catch more than their shares because the maximized profit is lower than the profit at the quota. When the stock is severely depleted (when the value of B' is very low), the fishers cannot make a profit from the fishery and do not go fishing.

MIXED STRATEGIES RESULTS: INFLUENCES OF r AND B' ON FISHERS' PROBABILITY TO COOPERATE

To see the influences of r and B on the fishers' cooperative behavior, consider either fisher A's or B's probability to cooperate in Figure 11. The fishers' probabilities to cooperate are labeled by two digits, representing the probability to cooperate for fisher A and B respectively. For example, the label 7, 9 indicates outcomes where fisher A's probability to cooperate (p_A) is 0.7 while fisher B's probability to cooperate (p_B) is 0.9. In general, the fishers' probabilities of cooperating increase as the value of r increases but decreases as the value of B' increases. However, this trend with respect to r and B' applies only to some ranges of values for r and B'. For example, fisher A's probability of cooperating at the value of B' = 0.58 is an increasing function of r for $0.00 < r < 1.79$. But for higher values of r, the probability is a decreasing function of r. Likewise, fisher A's probability to cooperate at the value of r = 1.80 is an increasing function of B' when the value of $0.42 < B' < 0.75$, but is a decreasing function of B' for the higher values of B'.

The incidence of non-linearity in the fishers' probabilities to cooperate relative to the biological parameters, r and B', can be rationalized in the same fashion as in the previous analyses—by considering the profit that the fishers will gain at the given values of the parameters in the model. For a comprehensive understanding, follow fisher A's probability to cooperate at a fixed value of B' = 0.61. The probability increases as the

Figure 11. Probabilities for cooperation of fisher A and B across the ranges of r and B', given $b_A = 0.7$, $b_B = 0.9$, and rho = 6.



value of r increases, within the range of the values of $0.00 < r < 1.79$. For the values of $r > 1.79$, the probability decreases. Fisher A's tendency to cooperate, which is normally low, becomes even lower because of the higher value of r. Consequently, he becomes less cooperative when the stock is extremely productive and variable.

Now, consider the influence of B' on fisher A's probability to cooperate by following his probability at a fixed value of $r = 1.64$. As the value of B' decreases the profit from the fishery decreases, especially the excessive profit. Fisher A, whose tendency to cooperate is low, will have less incentive to catch more than his share and becomes more cooperative as the value of B' decreases. However, for $B' < 0.43$, instead of increasing, fisher A's probability to cooperate drops from 0.8 to 0.7 until $B' = 0.37$. The excessive profit in this range of B' is less than that at higher values of B'. Fisher A consequently becomes less cooperative. At lower values of B' profit at the quota is greater than the maximized profit, which consequently forces the fishers to cooperate (the negative (cooperative, cooperative) outcomes). The maximized profit keeps dropping as the value of B' move towards 0.00, where the stock is completely exploited. The fishers no longer make a profit and stop fishing.

For the comparison between fisher A's and B's probabilities to cooperate, consider both fishers' probabilities to cooperate at a fixed value of r and B'. Although fisher A has a higher tendency to cooperate than fisher B ($b_A = 0.7$ versus $b_B = 0.9$), fisher A always has lower probability to cooperate. Recall that in the analysis of the influence of r and B' on the strategy outcomes of the game fisher A is more likely to cooperate than fisher B. In contrast, the analysis of the influences of r and B' on the fishers' probabilities to cooperate shows that fisher A has a lower probability to cooperate. Both the strategy outcomes and the fishers' probability to cooperate depend on the biological parameters and the fishers' tendencies to cooperate. The difference in how the strategy outcome is specified versus how the probability to cooperate is specified is that the outcome is based upon each fishers' own tendency to cooperate while the probability is based upon his opponents' tendency to cooperate. Therefore, the strategy outcomes work in an opposite manner from the probabilities to cooperate.

Fisher A's probability to cooperate depends on fisher B's payoff:

$$pA = \frac{\pi B_{cc}}{\pi B_{nc} + \pi B_{cc} - \pi B_{cn}}$$

When fisher A is facing an opponent, fisher B, who has a low tendency to cooperate, fisher A will have a lower probability to cooperate. With the lower tendencies to cooperate, fisher B's cooperative payoff is lower than that of fisher A; while his non-cooperative payoff (πB_{nc}) is higher than that of fisher A. Consequently, fisher A's probability to cooperate is lower than that of fisher B. An implication of this surprising result is that given a situation where the fishers are unsure about the decisions of one another, fisher A, who has a high tendency to cooperate, is less likely to play the cooperative strategy because fisher A knows that fisher B has a low tendency to cooperate. He also knows that with a lower tendency to cooperate, fisher B is more likely to play a non-cooperative strategy as the value of r increases. On the average, it would be better off for fisher A to play mixed strategies with low probability of playing a cooperative strategy, especially when the stock is highly variable. Meanwhile, fisher B, who is facing an opponent with a high tendency to cooperate, would be aware that fisher

A may play a non-cooperative strategy, which will result in zero profits for both of them. Similarly, on the average, it would be better for him to play mixed strategies with a high probability of playing a cooperative strategy.

VI. DISCUSSION AND CONCLUSIONS

In previous chapters, I presented analyses of the fishery model to answer the questions of interest, mainly whether the biological parameters, intrinsic growth rate (r) and stock size (B), influence the outputs from the fishery model, the strategy outcomes of the game and the fishers' probabilities to cooperate. The results of the analyses demonstrated that the biological parameters influence the model output. Because of the complexity of the fishery model, however, the influence of the biological parameters on the model output can only be inferred after specifying the other parameters in the models. The fishery model is a deterministic abstraction of real fisheries, which are stochastic systems that involve uncertainty. Many parameters in the system should be treated as random variables, including the profit/cost ratio and the fishers' tendencies to cooperate. These parameters influence the model output, as do the biological parameters.

Theoretically speaking, we would like to statistically test which parameter plays a significant role in the model. Ideally, we would like to prove that the parameters of interest significantly influence the model output so that we can fix the values of the other parameters without concern that the outcome will be affected. However, this method is unsuitable for the fishery model because the model output appears to depend on all parameters.

Even though the fishery model was primarily developed for understanding fishers' cooperative behavior, it would be beneficial if the model could also be used to make predictions. For example, a question for model prediction could be: "What is the probability of the fishers' cooperation when the stock is highly productive?" Without knowing whether r is the most crucial parameter that influences the model output, it is impossible to predict the probability of the fishers' cooperation. A general prediction cannot be made because r is not the only parameter that influences the output from the fishery model. Different values of the other parameters yield different model output. Then, the answer to the question of the fishers' probabilities of cooperating when the stock is highly productive depends on the values of the other parameters, for instance, whether there are high values for the profit/cost ratio and the fishers' tendencies to cooperate.

Despite the inability to predict the exact likelihood of the model output in relation to certain parameters of interest, the fishery model provides insight into important details of fisher's cooperative behavior. It is also capable of answering many questions of concern in fisheries management. The fishery model can do more than just answer the questions posed at the very beginning of this thesis.

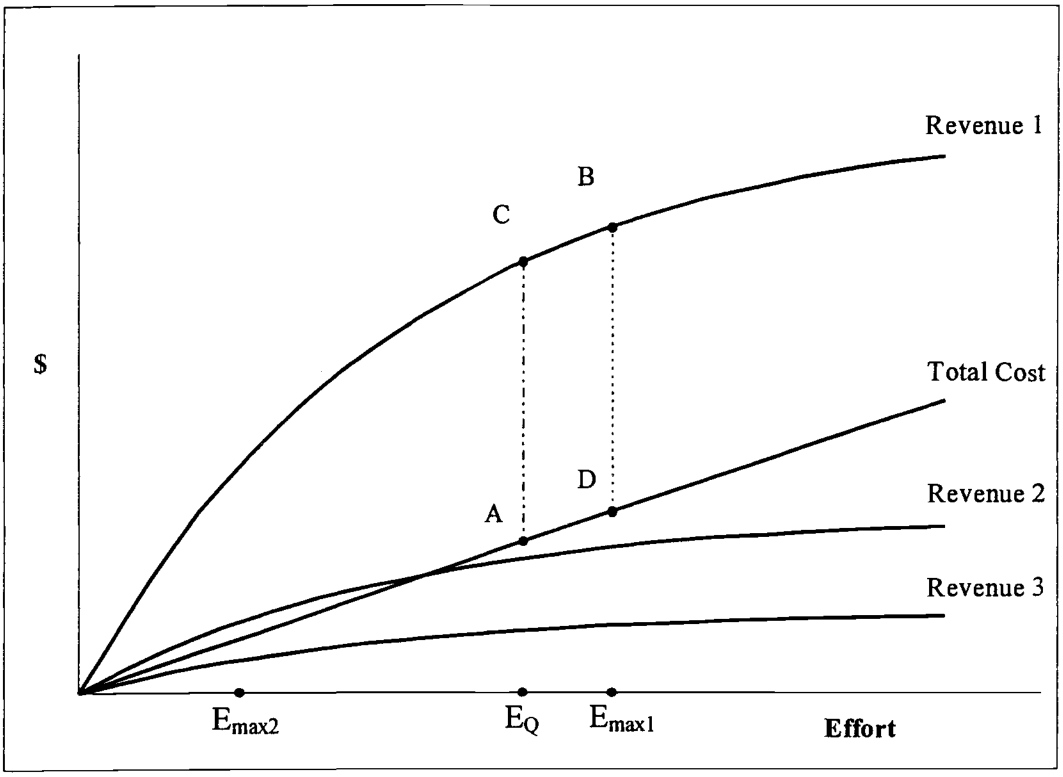
In the present chapter I discuss implications of the fishery model and, subsequently, draw conclusions from this study. The discussion is specific to the interpretation of the fishery model from the perspectives of economics and game theory. To conclude this thesis, I concentrate on the applicability of the fishery model. I also compare and contrast the conclusions drawn from this study with other studies. Further, I compare the conclusions from this study with those from a case study of Japanese co-management. In the last section on this chapter, I give suggestions for future research.

DISCUSSION

The fishery game sets up a situation where its members become suspicious of one another regarding their cooperative commitment. Despite such a dubious environment for cooperation, the outcomes of the fishery game are not necessarily always mixed strategies. They could potentially be any strategy outcome, including, surprisingly, cooperative strategy outcomes. Which parameters of the model drive the fishers to decide on a particular strategy cannot generally be determined because of the complexity of the fisheries system and the many parameters that are involved. However, one index that we could use to foresee a potential outcome of the game is the expected profit that the fishers gain by playing their best response strategy.

The results show that the fishers' decisions to cooperate depend on the profit that they perceive they will gain from being cooperative. The expected profit is a function derived from the parameters r, B', b_A, b_B, and rho. These parameters determine the fishing situations and profit information, which the fishers use to make a cooperative decision. The logic of specifying the strategy outcomes for the game is simply based upon the fishing situation. For example, if their expected cooperative profits are low, the fishers are less willing to cooperate. Figure 12 shows profits as a function of fishing effort from a fishery corresponding to three different fishing situations. Revenue 1 is the fishers' gross incomes when the fishing situation is highly profitable, while revenue 2 is less profitable and revenue 3 is unprofitable. E_{max1} and E_{max2} are the levels of effort that produce the maximized profit for revenue 1 and 2, and E_Q is the effort at the quota. The maximized profit corresponding to revenue 1 is the line segment BD and the profit corresponding to the quota for revenue 1 is AC.

Figure 12. Cost and revenue as a function of effort for three fishing condition: (1) normal profit; (2) low profit; and (3) no fishing.



Revenue 1 is the situation where the fish stock is highly abundant and price is high or cost is low. The fishers make reasonable profits when catching their quota shares but the maximum profit from the fishery is higher than that of the quota (BD > AC), which provides an incentive for the fishers to catch more than their shares. If this situation occurs, the game outcome tends toward mixed strategies, especially when the fishers have low tendencies to cooperate.

In the second fishing situation the fishery is less profitable due to fish scarcity, low fish price, and/or high fishing cost. Although the revenue at the quota is relatively high when compared to revenue from fishing at E_{max2}, the profit at the quota is negative because the fishers are fishing beyond the open access level. It is better for the fishers to catch less than their quota shares, otherwise they lose money. Technically, the fishers end up being cooperative, but I specify this case as a negative (cooperative, cooperative) outcome.

The last situation is when the fishers do not go fishing. The fishery is completely unprofitable. This is most likely to happen when the stock is scarce. The profit from fishing is always lower than the total fishing cost.

In contrast to the strategy outcomes, the probability outcomes within the mixed strategies space indicate that fisher B, who has the lower tendency to cooperate, has a higher probability to cooperate than fisher A. One may feel that this result is awkward. Intuitively and generally, we would expect that fisher A, who was the higher tendency to cooperate, should be more likely to play the cooperative strategy than fisher B. By their nature, the fishers who have high tendencies to cooperate should value cooperative payoffs more highly than those whose tendencies to cooperate are low. The fishers with high tendencies to cooperate are more conservative and less willing to gamble on the uncertainty of the stock. However, because the fishers' cooperation is studied under an application of game theory, one should keep in mind that the results should be interpreted strictly from the game theory point of view. There are reasons such results appear to contradict to our intuitive expectations.

When the strategic behavior of the fishers in a fishing cooperative organization is represented as a game, the fishers actually are the players of the game and their aim is to win--either to maximize their profits or minimize the damage that their opponent could possibly impose. In this regard, rather than focusing on the cooperative commitment, the fishers focus on how to play to win the game. The fishers choose how frequently they should play the cooperative strategy so that they can be as well off as possible given that the other fisher may or may not play the cooperative strategy.

In terms of playing a game, the tendency to cooperate in response to uncertainty about the fish stock has nothing to do with the players' choice of a particular strategy. The player chooses the cooperative strategy, for example, only when it can lead to his/her winning. In particular to mixed strategies, the outcome of the game depends on whether the probability of playing the cooperative strategy is considered to be the best response for the player. Playing the cooperative strategy with low frequency could lead to winning under some circumstances, whereas playing the cooperative strategy with high frequency could be better under other circumstances. The fishers' tendencies to cooperate represent the fishers' preference to behave in a certain manner in response to a certain circumstance. High tendencies to cooperate imply that the fishers prefer to cooperate but their final decision to play any strategy is based upon their expected maximum profits.

In the context of game theory, particularly with regard to mixed strategies, when a player plays his best response, at his equilibrium point, he imposes the condition that his opponent has the same average payoff regardless of what strategy the opponent plays. An example is the case of mixed strategies shown in Table 9. Using equations (27) and (30) the mixed strategy outcome equilibrium of the game is (0.524, 0.727), which corresponds to the equilibrium payoff of (0.030, 0.026). This means that when fisher A plays his best response by choosing the cooperative strategy with the probability of 0.524, fisher B will get an average payoff of $ 0.026 no matter which strategy fisher B chooses (Table 10). Likewise, when fisher B plays his best response by choosing the cooperative strategy with probability of 0.727, fisher A will get an average payoff of \$ 0.030 no matter which strategy fisher A plays (Table 11).

Table 9. Mixed strategy equilibrium outcome given $r = 0.4$, $B' = 0.6$, $b_A = 0.7$, $b_B = 0.9$, and rho = 6. Note that the expected payoffs are the profits from the fishing relative to the unfished stock and price (scaled by K and P).

Fisher B

		Cooperative	Non-Cooperative	
Fisher A	Cooperative	(0.032, 0.030)	(0.024, 0.050)	*0.524*
	Non-cooperative	(0.041, 0.022)	(0,0)	*0.476*
		0.727	*0.273*	

What this thesis finds is not unusual. How the two fishers react can be alternatively explained from perspectives other than the game theory perspective. Examples are the experimental studies of Dawes, McTavish, and Shaklee (1977) and Kelly and Stahelski (1970). These two studies aim at understanding individuals' cooperative behavior and individuals' expectations of what others would do, given people that are cooperative or competitive. Both studies found that individuals expect others to do the same as they do, regardless of their personalities. They expect others to cooperate when they, themselves, cooperate; they expect others to be uncooperative when they are uncooperative. Furthermore, the study of Kelly and Stahelski gives more details on differences in expectations regarding other people's actions. They found that cooperators expect that others could either be cooperative or competitive. As a consequence, the cooperators are cooperative when experiencing other cooperators, while they are more likely to become competitive when experiencing competitors. In contrast, the competitors expect others to be as competitive as they are. Therefore, competitors would play the game with the expectation that others are likely to do the same as they do, and play the non-cooperative strategy.

Table 10. Fisher B's payoffs at all possible mixed strategies combinations.

pA/pB	**0.000**	**0.200**	**0.400**	**0.500**	**0.600**	**0.700**	**0.727**	**0.800**	**0.900**	**1.000**
0.000	0.000	0.004	0.009	0.011	0.013	0.015	0.016	0.018	0.020	0.022
0.100	0.005	0.009	0.012	0.014	0.016	0.017	0.018	0.019	0.021	0.023
0.200	0.010	0.013	0.015	0.017	0.018	0.020	0.020	0.021	0.022	0.024
0.300	0.015	0.017	0.019	0.020	0.021	0.022	0.022	0.023	0.023	0.024
0.400	0.020	0.021	0.022	0.023	0.023	0.024	0.024	0.024	0.025	0.025
0.500	0.025	0.025	0.025	0.026	0.026	0.026	0.026	0.026	0.026	0.026
0.524	***0.026***	***0.026***	***0.026***	***0.026***	***0.026***	***0.026***	***0.026***	***0.026***	***0.026***	***0.026***
0.600	0.030	0.029	0.029	0.028	0.028	0.028	0.028	0.027	0.027	0.027
0.700	0.035	0.034	0.032	0.031	0.031	0.030	0.030	0.029	0.028	0.028
0.800	0.040	0.038	0.035	0.034	0.033	0.032	0.032	0.031	0.030	0.028
0.900	0.045	0.042	0.039	0.037	0.036	0.034	0.034	0.032	0.031	0.029
1.000	0.050	0.046	0.042	0.040	0.038	0.036	0.035	0.034	0.032	0.030

The fishers in the fishery model are equivalent to the competitors and cooperators in the studies mentioned above. The fishers who have high tendencies to cooperate are cooperators, while those who have low tendencies to cooperate are competitors. Therefore, it is not unusual that the fishers with high tendencies to cooperate play the cooperative strategy with lower probability than the fishers with low tendencies to cooperate. With the expectation that the others will do the same as they do, the fishers who have low tendencies to cooperate expect that the others will play the non-cooperative strategy, which will lead to zero profit for both parties. The fishers with low tendencies to cooperate tend to play the cooperative strategy with higher probability to avoid the zero profit.

Table 11. Fisher A's payoffs at all possible mixed strategies combinations.

pA/pB	**0.000**	**0.200**	**0.400**	**0.500**	**0.600**	**0.700**	***0.727***	**0.800**	**0.900**	**1.000**
0.000	0.000	0.008	0.016	0.021	0.025	0.029	***0.030***	0.033	0.037	0.041
0.100	0.002	0.010	0.017	0.021	0.025	0.029	***0.030***	0.033	0.036	0.040
0.200	0.005	0.012	0.019	0.022	0.025	0.029	***0.030***	0.032	0.036	0.039
0.300	0.007	0.013	0.020	0.023	0.026	0.029	***0.030***	0.032	0.035	0.038
0.400	0.010	0.015	0.021	0.024	0.026	0.029	***0.030***	0.032	0.035	0.037
0.500	0.012	0.017	0.022	0.024	0.027	0.029	***0.030***	0.032	0.034	0.037
0.524	0.013	0.017	0.022	0.024	0.027	0.029	***0.030***	0.032	0.034	0.036
0.600	0.014	0.019	0.023	0.025	0.027	0.029	***0.030***	0.031	0.033	0.036
0.700	0.017	0.020	0.024	0.026	0.028	0.029	***0.030***	0.031	0.033	0.035
0.800	0.019	0.022	0.025	0.027	0.028	0.029	***0.030***	0.031	0.032	0.034
0.900	0.022	0.024	0.026	0.027	0.028	0.030	***0.030***	0.031	0.032	0.033
1.000	0.024	0.026	0.027	0.028	0.029	0.030	***0.030***	0.030	0.031	0.032

Here is another explanation for the counter-intuitive results from the fishery game. The mixed strategy probabilities are suggestions to the players of what would be the best reaction for them under a certain circumstance of the game. The results in this thesis suggest that fishers who have a high tendency to cooperate will be better off if they are less likely to cooperate when facing an opponent who has a low tendency to cooperate. The fisher with a high tendency to cooperate perceives that his opponent is less likely to play the cooperative strategy. When the fisher with the high tendency to cooperate plays the cooperative strategy and his opponent plays the non-cooperative strategy, his fishing cost is higher than if his opponent plays the cooperative strategy. Therefore, it is better for him to be less likely to play the non-cooperative strategy. Meanwhile, the risk prone fishers will be better off if they are more cooperative, especially when r is high. Given a highly productive stock, the fisher is aware that his cooperative opponent will not always play the cooperative strategy, in which case both fishers will get zero profit.

To win a game does not necessarily mean getting the highest payoff because there are also constraints to consider, especially in a game where the players also need to defend themselves. In a strategic situation, what one player does could impact or damage the others. For example, the decision by one fisher to play the non-cooperative strategy in the fishery game imposes higher costs on the other fisher. It is better for the fisher paying the high fishing cost to play a strategy that helps minimize this damage. To maximize the payoff under this circumstance means minimizing the damage imposed by the opponent. The equilibrium outcome of the game is not the point where the players absolutely get the highest payoffs. It is the point where all the players play their best responses—getting the maximum payoffs while holding damages to a minimum. The best responses are the strategies that take into account the maximum payoffs while constraining the possible damages.

CONCLUSIONS

The fishery model answers the questions: (1) how do the biological parameters, intrinsic growth rate and stock size, influence cooperation; and (2) given heterogeneity in the fishers' tendencies to cooperate, how do the biological parameters influence cooperation. The biological (r, B'), social (b_A, b_B), and economic (rho) parameters are all significant in the model. Because the model is non-linear and has complicated interactions amongst all parameters, no general statement can be made if any one parameter is isolated from the others. Although this thesis concentrates on the influence of the biological parameters, their influence must be viewed in the context of the accompanying non-biological parameters.

The biological parameters have the opposite influence when both fishers have a high tendency to cooperate versus when both fishers have a low tendency to cooperate. When the fishers have a high tendency to cooperate, having an abundant stock (high value of B') promotes desirable outcomes from the game, even if the stock is highly productive and variable (high value of r). The fishers are more likely to cooperate when the stock is abundant. In contrast, when the fishers have a low tendency to cooperate, an abundant stock encourages the fishers to catch more than their quota shares, especially when the stock is also highly productive and variable.

This thesis finds that the profit/cost ratio (rho) plays a role in the fishery model as a promoter of the most widespread strategy outcomes. It scales up the most prevalent strategy outcome of the game, expanding the strategy outcome into wider ranges of r and B', e.g., extending the positive (cooperative, cooperative) outcome into larger ranges of r and B' when the game mainly yields this outcome. Hence, even in situations where the stock is highly productive or the stock size is low, there can be a good chance for cooperation if the profit is high.

Another focus of this thesis is the fishers' heterogeneity. It should be noted that the fishers' heterogeneity in this thesis differs from that in some studies, such as the study of Wilen (1970) that considers the fishers' heterogeneity in fishing effort. This thesis considers that fishers are heterogeneous in their tendency to cooperate. The heterogeneity contributes greatly to the outcome of the game when the degree of heterogeneity is high, when the two fishers' tendencies to cooperate are opposite. Because the fishers' tendencies to cooperate differ from one another, the (cooperative, mixed) and (mixed, cooperative) outcomes are the most frequent strategy outcomes. One fisher has the upper hand over the other in choosing which strategy to play, while the other has no better choice than playing the cooperative strategy. When the degree of heterogeneity is low, the outcomes are influenced by the fishers' tendency to cooperate. If both players have high tendencies to cooperate, the outcomes are usually desirable. However, if the players have low tendencies to cooperate, the outcomes are usually undesirable and dominated by mixed strategies.

The contribution of the fishers' heterogeneity to the strategy and probability outcomes are consistent with the conclusions of Kelly and Stahelski (1970) and Dawes, McTavish, and Shaklee (1977), that an individual's behavior is a function of the person and his/her social environment. An individual's action is likely to depend on what other people do. This thesis also concludes that the fishers' cooperative behavior is a function of their tendencies to cooperate and their social environment in the fisheries system. The fishers are more likely to cooperate if others do. If the cooperative organization is populated primarily by fishers whose tendencies to cooperate are low or by fishers whose tendencies to cooperate differ from one another, cooperation is unlikely to persist because the fishers' expectation of cooperation from the others is low. Another finding from this thesis that is consistent with the conclusion of Kelly and Stahelski is that the fishers who have low tendencies to cooperate perceive that others also have low tendencies to cooperate. Because of their awareness, the fishers with a low tendency to cooperate assume that other fishers will not cooperate and they actually have a greater probability of cooperation than fishers with a higher tendency to cooperate.

The case studies given in the literature review section support the findings of this thesis that biological parameters have an influence on fishers' cooperation. There are three main lines of support: (1) the evidence from the more successful management of the lobster fishery of the Katsuura FCA of adjusting and incorporating the limited entry and profit-sharing pool accounting system based upon biological concerns; (2) the evidence from the less successful management of Sukuma Bay FCA and the Hachinohe FCA that the regulations have never been adjusted and incorporated other supportive programs so as to deal with biological characteristics of fish stocks; and (3) the declining membership in the successful Nomaike FCA, which have resulted from uncertainty about the biological status of the fish stock.

The discussion and conclusions supply us information and understanding about fishers' cooperative behavior. At this point, the question is whether the abstract fishery model is applicable to real world situations. In traditional modeling, researchers need to validate their models. In broad terms, model validation is a process of testing how close a model is to the real system that is being studied (Gass, 1983; Heafner, 1996; Shannon, 1975). Because of the lack of sufficient information about real fisheries co-management systems, a rigorous validation of the fishery model is impossible at this time. Alternatively, I will use what information exists about real fisheries co-management systems to show that the model seems to be valid and applicable. In the following section I demonstrate that, rather than simply answering the questions posed at the beginning of this thesis, an additional contribution of the fishery model is its application to fisheries co-management.

APPLICATIONS OF THE FISHERY MODEL

The fishery model is developed for understanding the particular influence on fishers' cooperation of the biological characteristics of the fish stock. Its application is, therefore, primarily for helping fishery managers understand various aspects of a fishery cooperative. Another benefit that we can potentially gain from the model is suggestions for management.

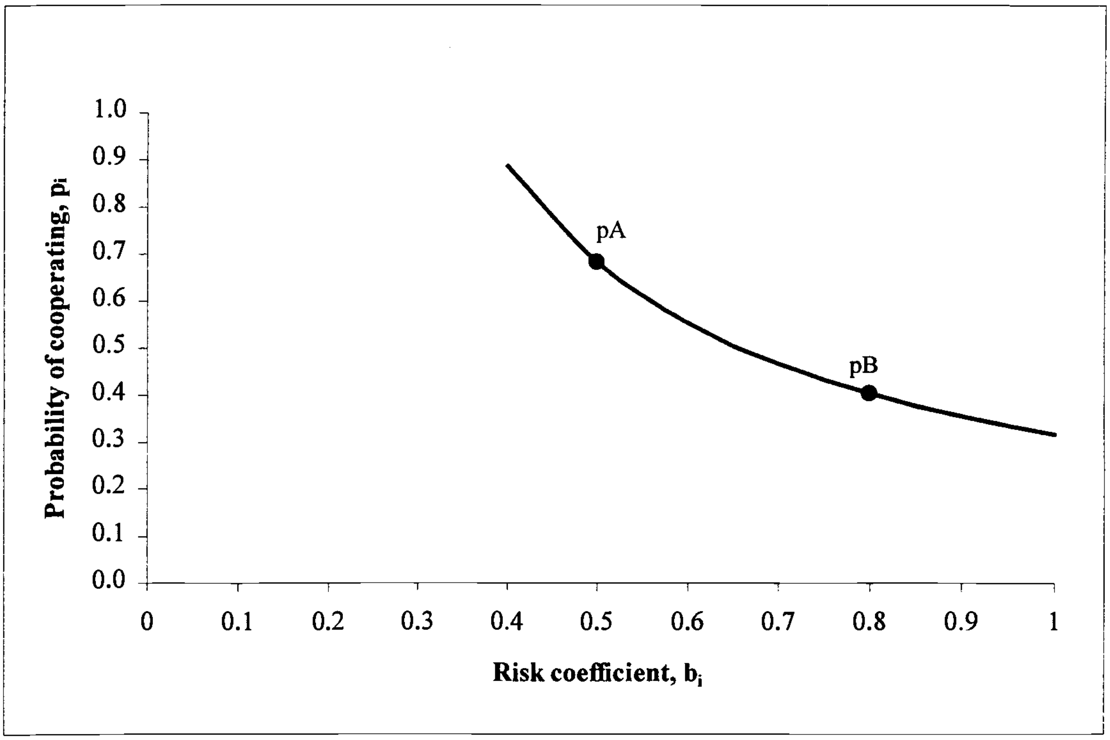
Understanding Fisheries Cooperative Systems.

In a fisheries cooperative, the fishery manager has ideas about the status of the fish stocks, prices for fish, costs of fishing, and fishers' tendencies to cooperate. The manager can apply the fishery model to project whether cooperation will continue and answer questions of concern about the current system such as: how much cooperation we are having; is it possible for the manager to push the system to a desirable outcome; which parameter(s) can the manager control to perturb the system towards a desirable outcome; and how much work does the manager need to put in so as to get a desirable outcome? These questions can be answered directly by using estimates for r, B', fish price, fishing cost, and the fishers' tendencies to cooperate as inputs to the fishery model. The model also allows the manager to look at strategy outcomes or probability outcome profiles for ranges of r and B', as presented in the results section. The outcome profiles are advantageous when the manager is unsure about the precise values for r and B' or when the manager considers that the values of r and B' may change.

Commercial fishing is a business involving considerable uncertainty, which is a consequence of variability in catch rates, stock sizes, biological parameters, equipment failure, fish prices, weather, quality of inputs, and internal and external institutions (Gates, 1984; Hildén and Kaitala, 1991; Plourde and Bodell, 1984). The uncertainty in fisheries results in various forms of fishers' behavior. The fishers' response to uncertainty has not been studied extensively, especially the uncertainty caused by biological parameters, such as intrinsic growth rate and stock size. Most fisheries researchers have traditionally treated these sources of uncertainty as constant parameters or deterministic variables in the fishery systems under study. However, it has been recognized that biological parameters are not constant over time (Hildén and Kaitala, 1991; Sissenwine, 1984a). Their values may vary seasonally or annually depending upon environmental changes. Within a certain period the manager will be unsure about the real values of the biological parameters because they may have changed. The outcome profiles provide the manager a potential scope of outcomes for likely ranges of values for r and B'.

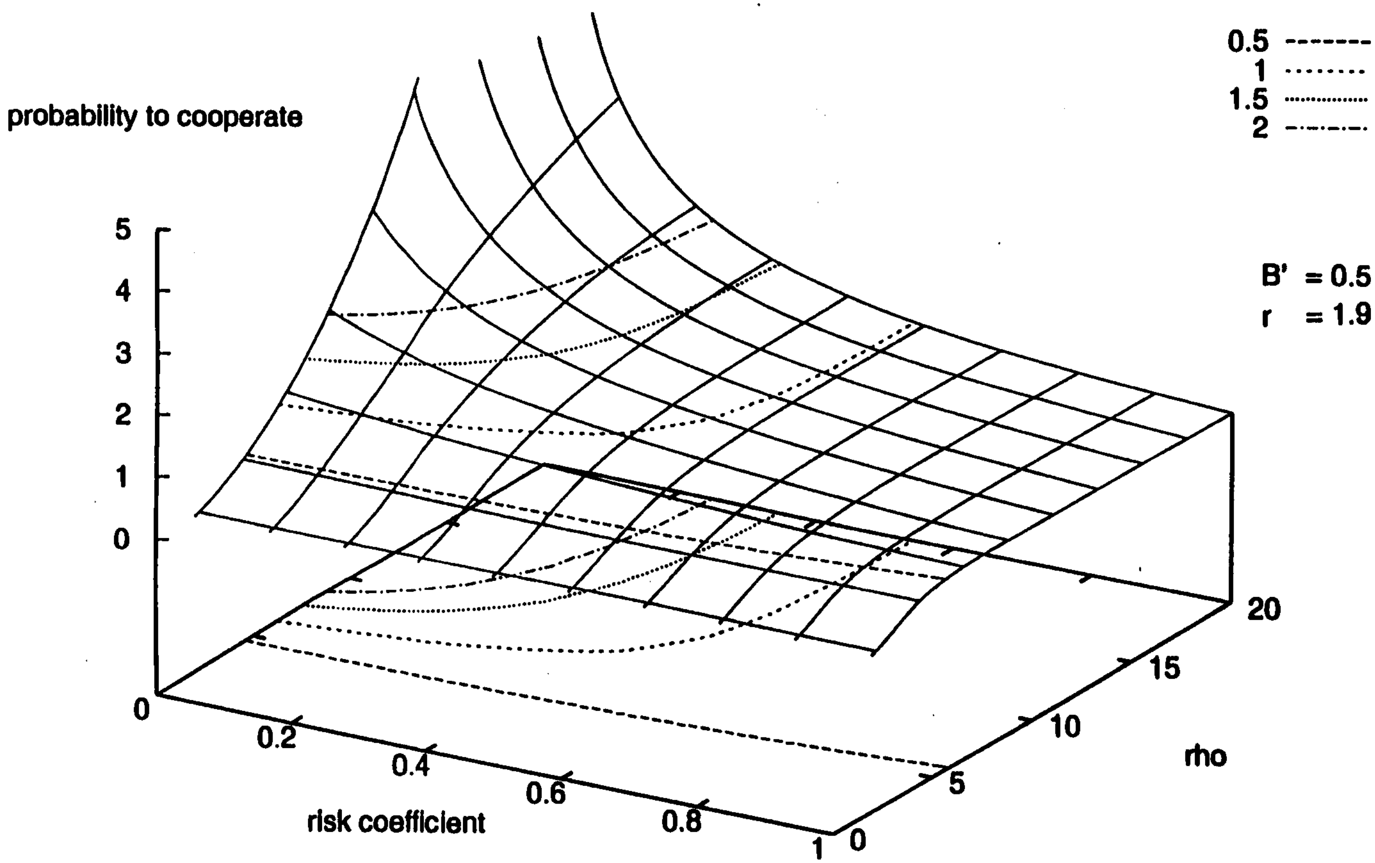
In the worst case, wherein the manager cannot obtain all the information needed for the model, he/she can use the available information and focus on the outcome profile over ranges of values for the unavailable parameters, possibly including their actual values. For example, if the fishers' tendencies to cooperate are unobtainable, the manager can look at the outcome profile versus the likely range of values for the fishers' tendencies to cooperate. Recall that the fishers' probabilities to cooperate are calculated using the same parameter values (r, B', and rho). The only difference between the equations for the two fishers is b_i (b_A versus b_B). Because the values of b_A and b_B are in the same range from 0 to 1, the fishers' probabilities to cooperate p_i (p_A and p_B) behave identically over a given range for b_i as shown in Figure 13 for the range of b_i from 0.4 to 1, given r = 0.2, B' = 0.7, and rho = 13. For the values of b_i less than 0.4, the fishers' probabilities to cooperate are equal or greater than one, which means the cooperative strategy is dominant. If the fishers are homogeneous, their probabilities to cooperate are the same and the probability outcomes for both fishers are at the same point on the outcome profile line. If the fishers are heterogeneous, their probabilities to cooperate are located at different points on the line. For example, suppose the manager believes that fisher A has a lower tendency to cooperate than fisher B ($b_A > b_B$) and that the risk coefficients are approximately $b_A = 0.8$ and $b_B = 0.5$. The probability that fisher B cooperates (p_B), corresponding to fisher A's risk coefficient of 0.8, is roughly 0.4. Meanwhile the probability that fisher A cooperate (p_A), corresponding to fisher B's risk coefficient of 0.5, is roughly 0.7. Therefore, given a fishery that has a moderately fast growing stock with relatively high stock size and high profit/cost ratio, the fishery model suggests that cooperation is not likely when the fishers are heterogeneous, especially when one fisher has a low tendency to cooperate relative to the other. Moreover, we can see from the probability outcome profile that the wider the gap between the two fishers' risk coefficient the less likely that both fishers will cooperate. The probabilities for the two fishers move away from one another.

Figure 13. Probability outcomes at a given range of b_A or b_B, given r = 0.2, B' = 0.7, and rho = 13



In the case that information on the profit/cost ratio is also unavailable, the manager can apply the fishery model to generate an outcome profile between the fishers' probabilities to cooperate versus the profit/cost ratio and b_A or b_B. The example shown in Figure 14 shows fisher B's probability to cooperate (p_B) across ranges of values for the fisher A's risk coefficient (b_A) and rho, given the values of r = 1.9 and B' = 0.5. Each of the dotted lines represents a contour of constant probability. The outcome profiles

Figure 14. Fisher B's probability to cooperate across the values of fisher A's risk coefficient and rho.



represent the probability outcomes over the range of b_A from 0 to 1, and the range of rho from 0 to 20. The model tells the manager that if the fishery has a fast growing stock that has been fished down to the MSY level (B = ½*K), the following events may be expected: (1) There is about a fifty-fifty chance that cooperation will continue when the profit/cost ratio is low, regardless of the fishers' tendencies to cooperate (dotted line labeled 0.5); (2) The boundary between the dominant cooperative and mixed strategies is the contour line where the probability equals one. The boundary tells us that if the fishers have high tendencies to cooperate ($b_i < 0.5$) cooperation is very likely provided the profit/cost ratio is not very low (rho > 5).

Suggestions from the Fishery Model for Co-management

The fishery model is developed based upon a fishery that is managed with a quota system. Any fisheries co-management that uses a quota system can benefit directly from suggestions from the fishery model. For a fishery cooperative that relies on a system not based on a harvest quota the fishery model can be modified and adjusted to suit the system. The following are suggestions that the managers can use to achieve secondary benefits from the fishery model.

The managers can use the fishery model to adjust restrictions on the quota so as to get legitimate regulation. When the quota is high, the fishers have less incentive to exceed their quota shares because the profit at the quota may be close to the maximized profit,making the fishers indifferent between the two profits. This finding is similar to evidence that Hønneland (2000) finds in his investigation of how Norwegian and Russian fishers abide by their cooperative fishing regulations. He notes that when the fish stock is abundant and the quota is high, the fishers have no incentive to fish illegally.

Pollnac and Carmo (1980), who studies Portuguese fishers' attitudes toward cooperation, also found similar evidence. They concluded that when a fish stock is increasingly abundant the fishers feel less uncertain about the stock and they become more conservative in their fishing. They also suggest that, together with abundance of the stock, good communication will reduce lack of trust, resulting in a higher tendency to cooperate.

Under normal circumstances where the fishery is profitable and the profit at the quota is less than the maximized profit from the fishery, the fishery model suggests that one way to promote cooperation is by increasing the quota because this action reduces the gap between the maximized profit and the quota profit. When the quota profit is very close to or at the same level as the maximized profit, the fishers have no reason to exceed their quotas. When a fishery is healthy and the maximized profit from the fishery is high, the difference between the maximized profit and quota profit is large. The extra profit provides a incentive for the fishers to catch more than their quotas. The manager should recognize this situation and be prepared for rule breaking. The fishery model further suggests that more cooperation can be gained by reducing the gap between the maximized profit and the quota profit.

However, increasing the quota may in the long term result in an overexploited stock. Theoretically, the quota, which is derived from the estimated fishing rate that will produce the MSY, represents a long term commitment to stock sustainability. It is the level of catch that conceptually guarantees sustainability. If the manager tries to satisfy the fishers in the short run and insure their cooperation by increasing the quota, the manager should be aware of the trade off and consequences from doing so. The manager should ask himself whether he wants to risk stock overexploitation.

A critical point that the managers should be concerned with is high fish price, especially if the members of the cooperative have low tendencies to cooperate. This thesis finds that when fish price is high the fishers with low tendencies to cooperate have more incentive to exceed their quota shares. As the price goes up, the maximized profit increases as well as the profit at the quota. The gap between the maximized profit and the quota profit remains wide, which provides an incentive for the fishers to catch over their quota shares. But if we increase the quota, only the quota profit is higher. The gap between the maximized profit and quota profit narrows and the incentive to catch over the quota decreases.

LIMITATIONS OF THE FISHERY MODEL AND SUGGESTIONS FOR FUTURE RESEARCH

Like other models the fishery game is based on assumptions. These assumptions limit the model's capability to answer certain questions. In this section, I specify some of the limitations of the fishery model and offer corresponding suggestions for future research.

The fishery model has limitations on its application to fisheries cooperatives that for practical purposes do not use a harvest quota system. Most fisheries co-management systems focus on territorial use rights and licensing. Only a few cooperatives use harvest quotas in their management, for example, the Gull Haven and Shoal Harbor Cooperatives in the US Eastern Seaboard area, and the UK cooperatives known as producers' organizations (Jentoft, 1989; McCay, 1980). The Japanese case studies reviewed in this thesis are examples of cooperative systems based on territorial use rights and licenses. A common problem arising in fisheries cooperatives, as in the case studies, is illegal fishing in prohibited fishing grounds. The problem of illegal fishing appears to be a consequence of improper exercise of fishing rights and enforcement, compounded by the problem of declining fish stocks. Each fishing village in a prefecture is granted fishing rights in a different type of fishery and different fishing grounds. The fishers in one village illegally fished in fishing grounds other than their own because of high prices and declining stocks. On economic grounds it seems obvious that the different levels of profit between the two fisheries was the driving force for the illegal fishing activity. There is no other evidence to explain the fishers' behavior. The problem is similar to the one modelled in the fishery game in that economic forces can outweigh the cooperative commitment. However, the driving force for such a breakdown in commitment is different than in the fishery game. Modifying or adjusting the fishery model to capture this problem appears to be inappropriate. Rather, a spatially explicit model without quotas is needed.

Because the fishery game is a one period game, the fishery model cannot address long term effects of either cooperation or stock sustainability. For example, if the managers decide to promote cooperation by increasing the quota it is not certain that over the long term this action would result in stock depletion. Likewise, if the managers' primary decision is to sustain the stock by imposing restrictive fishing regulations, the fishery model cannot show the long-term consequences of excessive harvests due to cheating. Restrictive regulations always create pressure on the fishers, which can break down cooperation with the harvest quota. The fishery model could be run iteratively, using the unharvested fish plus recruitment as initial stock size for each successive period.

In the fishery game I assume that there is no enforcement of the harvest quotas or penalties for cheating. The original idea of omitting a penalty from the fishery game was to understand when and how cooperation would voluntarily emerge in a fisheries cooperative. In addition, having a penalty in the fishery model means that the fisheries cooperative must have a monitoring system, which is costly and contradicts the rationale for co-management. A major benefit of co-management is supposed to be low costs of enforcement. The fishery model does provide an understanding of natural and voluntary cooperative behavior, which was the primary aim for this thesis. However, this assumption may be unrealistic when we want to look at how fishers react to the existing systems, as most cooperatives require their members to directly monitor their compliance with regulations.

A penalty could be imbedded in the non-cooperative payoff function. For example, the penalty could be specified as a probability of getting caught, with higher profits resulting in a greater chance of the penalty and hence a lower payoff on average. However, a real fishing cooperative might have a more severe penalty, such as membership cancellation for fishers who violate their harvest quotas. In this case we could set up zero profit to represent the cancellation (which means the game ends for those fishers) once the violation is detected. In this scenario, we need to specify in the model how the violation would be detected during the fishing season.

Because the fishery game only has two players, the fishery model cannot directly examine the case of more than two players. The fishery model still may be reliable for a cooperative where there are more than two fishers. Especially for the case where all the fishers are reasonably homogeneous in their tendencies to cooperate and the case where the fishers can be classified into two distinct groups whose tendencies to cooperate are different. The fishery model could be extended to an n-person game but the mathematics would be much more complicated.

The assumption of zero profit for the (non-cooperative, non-cooperative) outcomes may be unrealistic for some fisheries because the fishers are limited in how much effort they can apply during a fishing season. The rationale for zero profit is that when both fishers decide to exceed their quota shares, they continue fishing until it is no longer worth their while to do so. Consequently, the fishers make normal profits of zero. However, the fishers may not be capable of taking the open-access level of harvest, in which case the non-cooperative payoffs will be greater than zero. Assigning this non-cooperative payoff is complicated because we do not know how much each of the fishers will catch. One way to deal with this problem is to assume that the two fishers have the same maximum amount of fishing effort that they can employ during the fishing season. The non-cooperative payoffs would be determined by this maximum level of fishing effort or the effort required for open-access, whichever level of effort was smaller.

The fishery model only considers two biological parameters, the intrinsic growth rate and the stock size, because those two parameters are the main contributors to stock fluctuation and availability of fish for the fishery. There may be other biological characteristics that should be included in the fishery model, either for better understanding of fishers' cooperation or for finding better management programs, for traits may result in certain responses from the fishers that could harm the stock and cause problems in the cooperatives because stocks with differing traits may be differently susceptible to fishing pressure. For example, lobsters are an organism with special biological characteristics. Their tendency to aggregate and be relatively immobile results in high competition among fishers to be the first in getting to and taking control over the fishing grounds. Knowledge of this can contribute to better management if the managers can adjust regulations or introduce new management programs to deal with such problems, as in the Katsuura FCA that introduced a profit-sharing pool accounting system for its lobster fishery.

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